The collapse of NATM tunnels at Heathrow Airport

A report on the investigation by the Health and Safety Executive into the collapse of New Austrian Tunnelling Method (NATM) tunnels at the Central Terminal Area of Heathrow Airport on 20/21 October 1994

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First published 2000

ISBN 0 7176 1792 0

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Foreword

This report fulfils a commitment made by the Health and Safety Executive to publish - once legal proceedings were completed - the findings of our investigation into the tunnel collapses at Heathrow Airport in October 1994 during which many people were put at serious risk and from which the commercial losses were significant.

The report provides a compelling account of engineering failures in a complex construction project; and, specifically, failures to identify hazards and manage risks. Despite the complexity, most of the lessons are relatively straightforward. Put at its simplest, the incident could have been prevented if proper consideration had been given to identifying the hazards and consequences, and to controlling the risks.

It must never be forgotten that construction work can result in major incidents which put workers and the public at risk. The means of preventing them are clear. It requires no more, but equally no less, than a total commitment by organisations, their directors, partners and senior managers, and the active involvement of all those at work including safety representatives, so as to:

- establish a culture in which health and safety is paramount;
- recognise that some construction processes have the potential to cause major incidents;
- put effective risk assessment, reduction and control at the core of robust health and safety management systems; and
- ensure that the key players - clients, designers, contractors and workers - work well together to secure the highest standards of health, safety and welfare.

The report provides the opportunity for action. Those involved in the industry must take account of the wider lessons and review their current arrangements to ensure that they will not be found wanting. Those involved in training have the benefit of an excellent case study from which to learn.

I commend this report to you, and the lessons it contains.

Kevin Myers
HM Chief Inspector of Construction
July 2000

Summary

The incident

1 One of the worst civil engineering disasters in the United Kingdom in the last quarter of a century occurred during the night of 20-21 October 1994 when tunnels in the course of construction beneath Heathrow Airport's Central Terminal Area (CTA) collapsed. They continued to collapse over the following days. The public and those engaged in the construction work were exposed to grave risk of injury. Workers were evacuated from the tunnels minutes before the first collapse. Some had been carrying out repairs to critical parts of a tunnel lining while others had been advancing a parallel tunnel. By remarkable good fortune no one was injured. Major short-term disruption to the airport followed. The Heathrow Express Rail Link project, of which the tunnels were a part, suffered a severe set-back as a result.

2 The so-called 'New Austrian Tunnelling Method' (NATM) and compensation grouting had been used. NATM was in use elsewhere at the Terminal 4 (T4) Station for Heathrow Express and in central London on parts of the Jubilee Line Extension Project. Another Heathrow project was about to use NATM for parts of a tunnel between T4 and the CTA. Immediately after the collapse, all NATM work was voluntarily suspended as a precautionary measure.

The response

3 The Health and Safety Executive (HSE) requested that NATM work should not recommence until the project teams were able to demonstrate that they could adequately control the risks to the workforce and to the public.

4 The Health and Safety Commission requested HSE to carry out a two-part investigation. First, HSE was asked to consider whether there were any broader health and safety implications concerning both the construction of NATM tunnels in the UK, and the safety of finished NATM tunnels when compared to tunnels constructed using different techniques. HSE's report *Safety of New Austrian Tunnelling Method (NATM) tunnels*[1] (the NATM Report) met that objective. Second, HSE was asked to investigate the causes of the Heathrow collapse and publish a report of the findings. This report fulfils that request.

The cause

5 The direct cause of the tunnel collapses was a chain of events involving:

- substandard construction in the initial length of the CTA concourse tunnel over a period of some three months;
- grout jacking that damaged the same length of tunnel plus inadequately executed repairs to it some two months before the collapse;
- the construction of a parallel tunnel in failing ground;

- major structural failure in the tunnels, progressive failure in the adjacent ground, and further badly executed repairs during October 1994.

There were weaknesses in the contingency and emergency procedures.

6 Hazards from the *in situ* (ie cast-in-place) construction of thin shell linings and the complementary use of compensation grouting were not identified by all the parties. Risk was not avoided or reduced through the contractual arrangements, the design of the permanent works and the NATM design. Risks were not controlled, during construction, through the 'defensive' systems (ie preventative management systems) used by the parties. The particular risks associated with remedial work were not recognised.

7 The collapses could have been prevented but a cultural mind-set focused attention on the apparent economies and the need for production rather than the particular risks. From the early stages of the project through to final collapse, there were failures to demonstrate the necessary level of care and serious errors were made. Warnings of the approaching collapse were present from an early stage in construction but these were not recognised.

8 Investigation has found that the incident exhibited all the hallmarks of an 'organisational accident'; that is, a multiplicity of causes led to the position where systems variously used by the client, designers and contractors failed and a major accident adversely affecting the safety of a large number of people occurred. There were undoubtedly human errors, but these were merely a consequence of foreseeable organisational failures. The causes of the incident were rooted in failures in 'defensive' systems that did not adequately deal with hazard identification, risk avoidance and reduction, and the control of remaining residual risks. Errors were made, leading to:

- poor design and planning;
- a lack of quality during construction;
- a lack of engineering control; and, most importantly
- a lack of safety management.

9 There were no effective arrangements for involving workers or for seeking their views on health and safety issues.

Legal proceedings

10 On 15 February 1999 at the Central Criminal Court (the Old Bailey), record penalties totalling £1.7 million were imposed at the conclusion of legal proceedings instigated by HSE. The principal contractor, Balfour Beatty Civil Engineering Ltd, was fined £1.2 million - at that time the biggest single fine for an offence under the Health and Safety at Work etc Act 1974.[2] Expert adviser, Geoconsult ZT GMBH of Austria, was fined £0.5 million. Both were ordered to pay contributions of £100 000 towards the prosecution's costs.

11 Balfour Beatty had pleaded guilty to alleged breaches of sections 2(1) and 3(1) of the Health and Safety at Work etc Act 1974[2] concerning a failure to ensure the safety of its employees during

construction of the tunnels and, similarly, other people, as a part of its undertaking in designing and constructing the tunnels at the CTA. The Crown took the decision not to pursue similar allegations concerning T4 in the light of guilty pleas to the CTA offences and offered no evidence on these. 'Not guilty' verdicts were returned on T4 as a consequence.

12 Geoconsult had pleaded not guilty to similar alleged breaches connected with its undertaking in designing and providing technical supervision during the construction of the tunnels at the CTA and at T4. In view of the decision taken concerning Balfour Beatty and T4, the Crown decided it would be inappropriate to proceed further with the T4 allegations. 'Not guilty' verdicts were returned on T4 as a consequence. Geoconsult was found guilty by a unanimous jury decision on the allegations concerning CTA. The trial judge said that Geoconsult's culpability was confined to aspects of design monitoring and interpretation of monitoring of the NATM tunnelling - and to a failure to warn. A subsequent appeal against conviction and sentence was dismissed.

Lessons to be learned

13 There are a number of salutary lessons. These must be learnt by the construction industry and put into effect so that further major disasters can be avoided.

- The potential for major accidents must be recognised and addressed by all parties through the effective use of hazard identification, consequence analysis and risk reduction strategies.
- New or unfamiliar technologies require rigorous understanding and assessment before they are adopted.
- Major projects carried out in close proximity to the public with the potential to cause significant harm to them require particular review.
- It is essential that organisational and human factors are taken into account when devising management systems to secure health and safety.
- Production pressures must be balanced by defensive precautionary systems.
- Demonstrable high levels of commitment to health and safety systems involving everyone at work, and including consultation with them and their safety representatives, are essential.

14 Those involved in projects with the potential for a major accident should ensure that they have in place the culture, commitment, competence, and health and safety management systems to secure the effective control of risk and the safe conclusion of the work. Had such strategies been successfully adopted at the Heathrow Express Project, unnecessary risk, disruption, delay and cost would have been avoided.

Introduction

The project

15 The Heathrow Express Rail Link Project provides a high-speed passenger service from London (Paddington) main line rail station directly to London (Heathrow) Airport.

16 The project was a joint venture between British Rail (now Railtrack plc) and BAA plc. Railtrack was responsible for a new junction with the main line linking London and Bristol and for work to the existing track. BAA was responsible for all other work. Heathrow Airport Limited, a wholly-owned subsidiary of BAA, was named as the client in the contract documents where BAA had the joint-venture lead.

17 Figure 1 shows the general arrangement at Heathrow. The link uses existing track from Paddington to a new junction north of the airport. A twin-track 'cut-and-cover' running tunnel carries the track to a point just north of the M4 motorway. Twin-bored running tunnels then link to the station at the CTA. A single-bored running tunnel extends the line to the T4 terminus.

18 The project received Government approval in principle in 1988. This was followed by a private parliamentary bill. There were a number of delays during the project's evolution due to funding constraints.

19 Heathrow Airport Limited's Engineering Projects Group initially led for BAA. The work and staff were transferred to BAA's Group Technical Services Division in early 1991. Taylor Woodrow Management Contracting Limited (Taylor Woodrow) was engaged as project manager and acted as construction advisers to BAA until about the time construction commenced. BAA variously engaged other advisers and consultants, including Mott MacDonald as principal designers.

20 The schematic drawings for the parliamentary stage suggested the use of tunnelling shields and segmental linings for the platform tunnels, and tunnel boring machines (TBMs) for the running tunnels. The possibility of using NATM was raised in 1989 by BAA's advisers. The project was subsequently taken forward using NATM for the station complexes. The remainder of this report deals solely with the two stations and NATM work.

21 The use of NATM for the first time in London clay was an understandable extension of the technique. Sufficient was known about the method and the behaviour of London clay for safe and economic construction to be achieved. Anticipated ground surface settlements, a key tunnelling consideration, were predictable by calculation to within a narrow range but were largely untested by experience. Concerns remained about NATM's ability to control and limit settlement, including beneath the existing Piccadilly Line tunnels. A trial tunnel was constructed early in 1992 to evaluate settlement and to demonstrate the NATM technique to UK contractors interested in bidding for the project.

22 Compensation grouting, another technique tried elsewhere but largely untested in London clay, was

being considered as a means for limiting settlement. It had been used once before in London clay in conjunction with a shallow tunnel but the technique was mostly applied to the shallow gravels overlying the tunnel rather than the clay. Although used elsewhere in Europe, it did not have a well-defined theoretical basis. It did not feature in the trial tunnel.

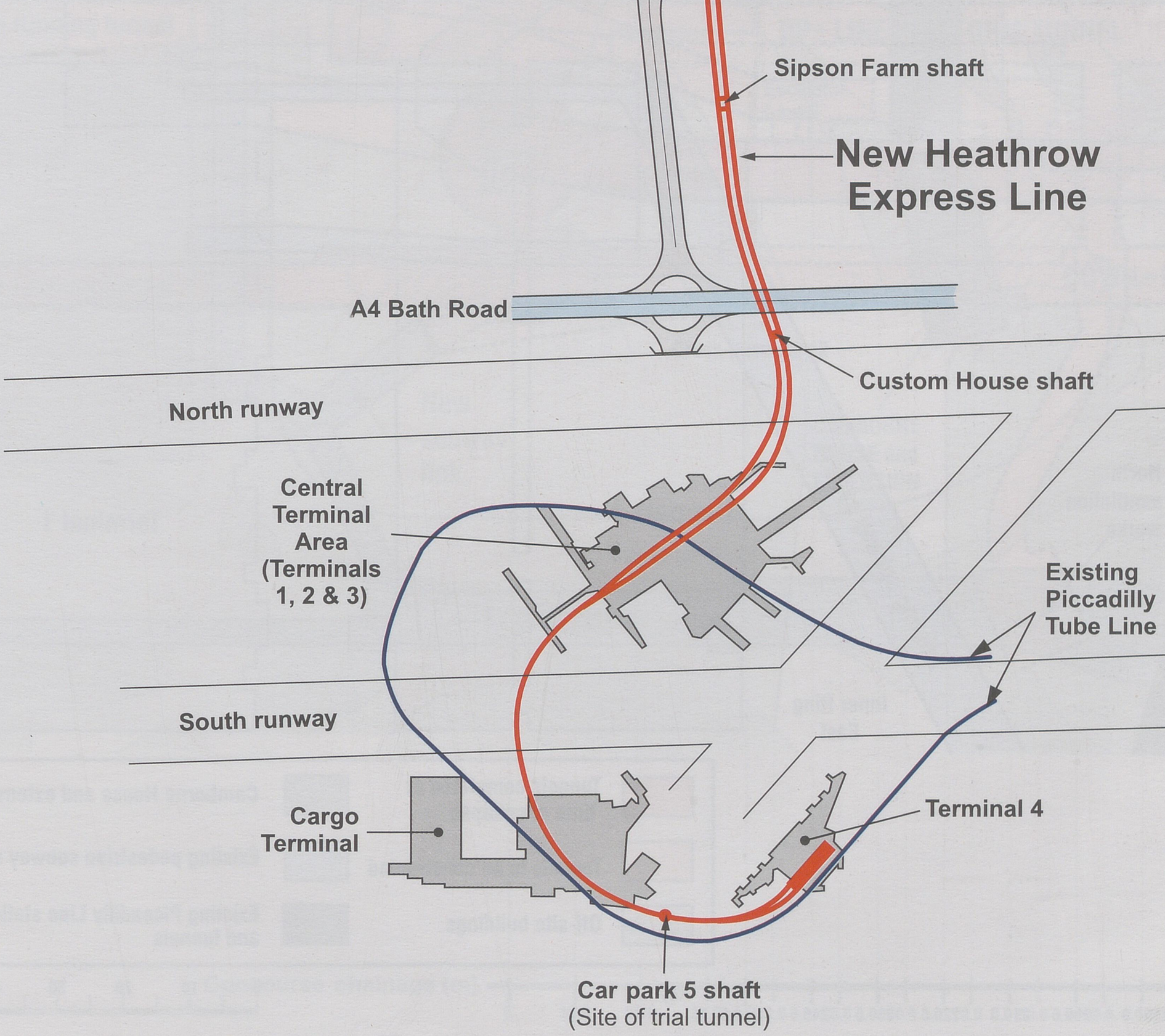


Figure 1 *Heathrow Express layout at the airport*

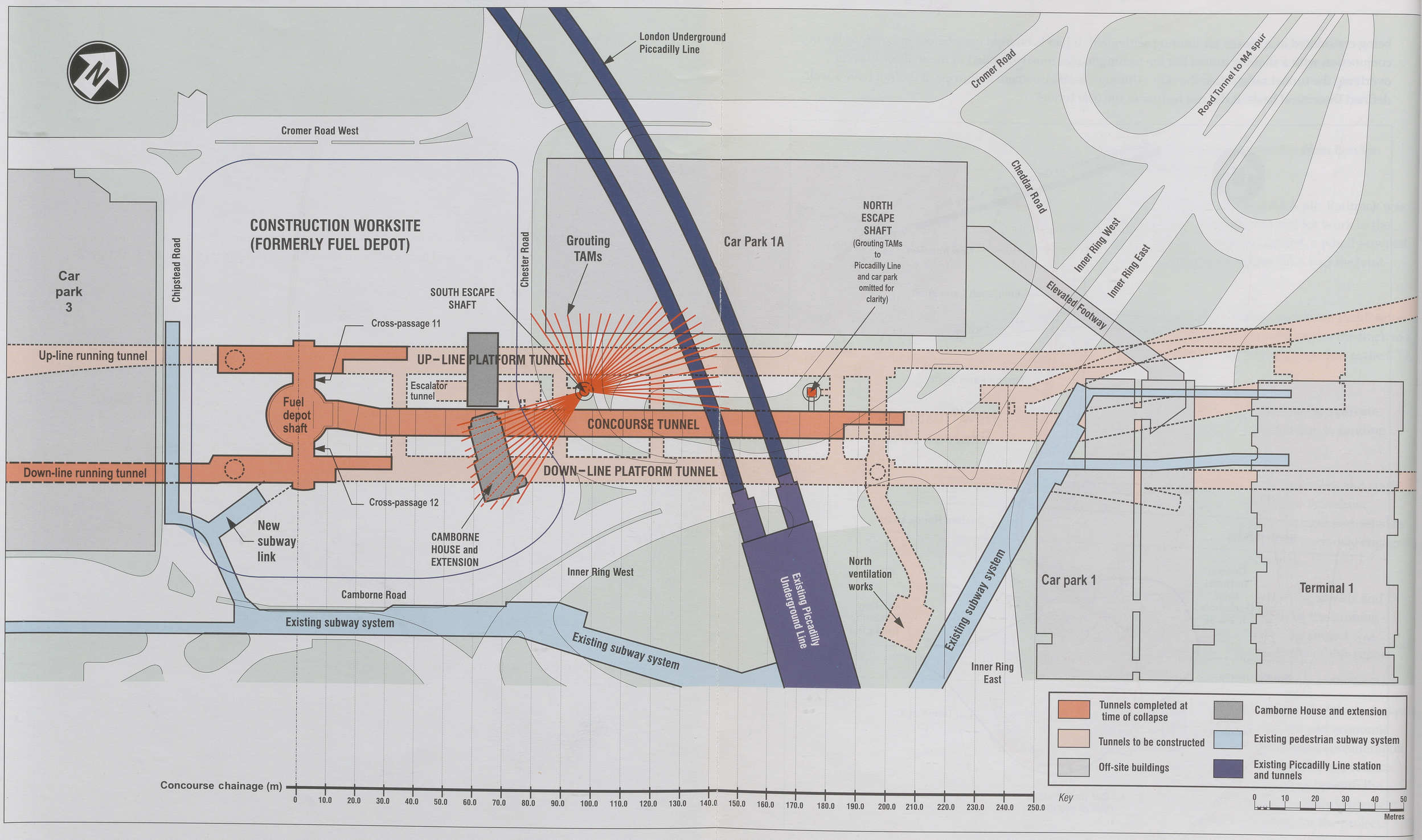


Figure 2 *Layout at Central Terminal Area*

The NATM stations

23 The stations at CTA and T4 had twin-platform tunnels separated by further tunnels - concourse tunnels - used for passenger circulation. When finished, the tunnels were to be some 8 m wide, 7 m high and have flattened inverts.

24 Part of the congested CTA is illustrated in Figure 2. This shows the locations of key buildings, the new Heathrow Express tunnels and shafts, and the existing Piccadilly Line and pedestrian subways. The new station was to link with the existing pedestrian subway system. An inclined tunnel - the escalator tunnel - was to have been constructed between the up-line platform and concourse tunnels. The concourse tunnel was offset towards the down-line tunnel at about chainage (ch.) 30 m of the concourse tunnel. ('Chainage' is used to identify a point along the axis of a tunnel defined by its distance from a fixed reference point. For the CTA concourse tunnel, the reference point was the centre of the fuel depot shaft, see Figure 2.) There were further smaller tunnels, mostly for the purposes of providing pedestrian links between the main tunnels and for ventilation. All of these tunnels, a nearby cross-over and turn-outs in the running tunnels were to be constructed by NATM. Figure 3 provides a three-dimensional view of the CTA station.

25 Construction of the CTA station was from an 'island' site. It was bounded by Cromer Road West, Chipstead Road, Camborne Road and Chester Road (Figure 2). Camborne House and its extension was one of two permanent buildings present within the contractor's work area. It was used as a site office. The other building, a workshop close to Camborne Road, was also used by the contractor. All three principal NATM tunnels were to extend outside the site boundary and pass along one side of car park 1A, under the Piccadilly Line and under the busy inner ring road used by traffic entering and leaving the CTA. Those parts of the tunnels constructed by the time of the collapse are heavily shaded in red in Figure 2. Those yet to be constructed are shown dotted and lightly shaded.

26 Figure 4 shows a longitudinal section of the CTA concourse tunnel, including Camborne House, the grouting subsequently placed beneath it, and the Piccadilly Line tunnels. The lower illustration shows a cross-section at Camborne House.

27 The CTA tunnels were to be constructed at a depth of some 30 m to the inverts. A 5 m deep bed of gravel, the Taplow gravels, overlaid a bed of London clay some 60 m thick (Figure 4). Groundwater was present in the lower levels of the gravel bed but the clay was sufficiently impermeable to prevent significant penetration to tunnel level.

28 A number of shafts were associated with the station complexes and with isolated ventilation and emergency escape points along the route of the running tunnels (including at Shepiston Lane, Sipson Farm and Custom House, Figure 1). Shafts were mostly constructed from precast concrete segments. The contractor opted to use NATM for the lower sections to ease the transition to the running tunnels. Short cross-passages associated with these shafts were also in NATM.

29 The 19 m diameter CTA fuel depot shaft (see Figure 2) derived its name from the previous use of the area as an aviation fuel distribution depot. The shaft had a heavy concrete base slab and was surmounted by a large subsurface concrete box independently supported on bored piles. There was a

smaller stepped box to provide a connection point for the NATM escalator tunnel (Figures 3 and 4). The large box and its piled foundations extended to the vicinity of the offset in the concourse tunnel, ch. 30. The shaft provided the principal means of access and egress to the underground CTA station works during construction.

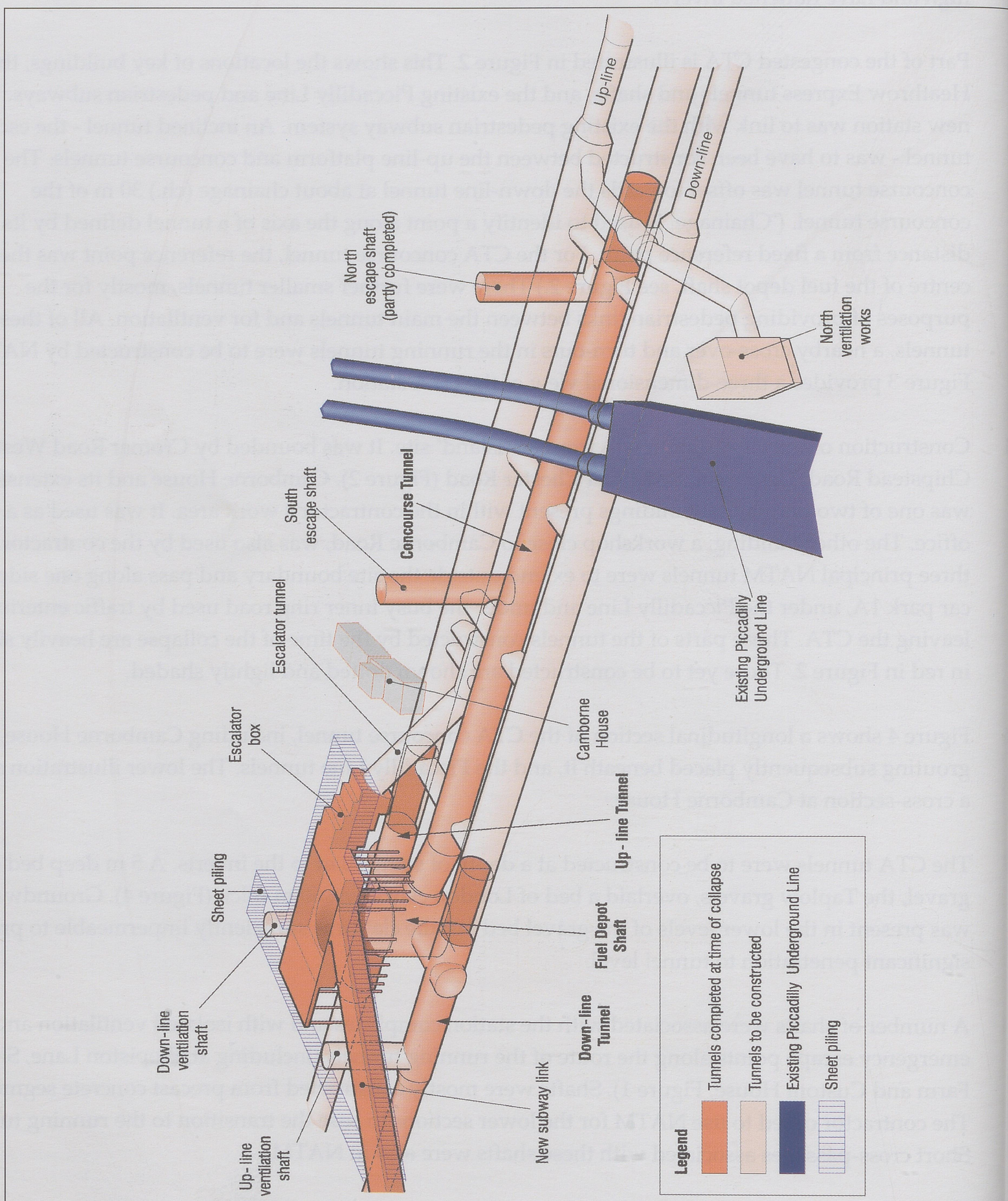


Figure 3 *Three-dimensional drawing showing the CTA station*

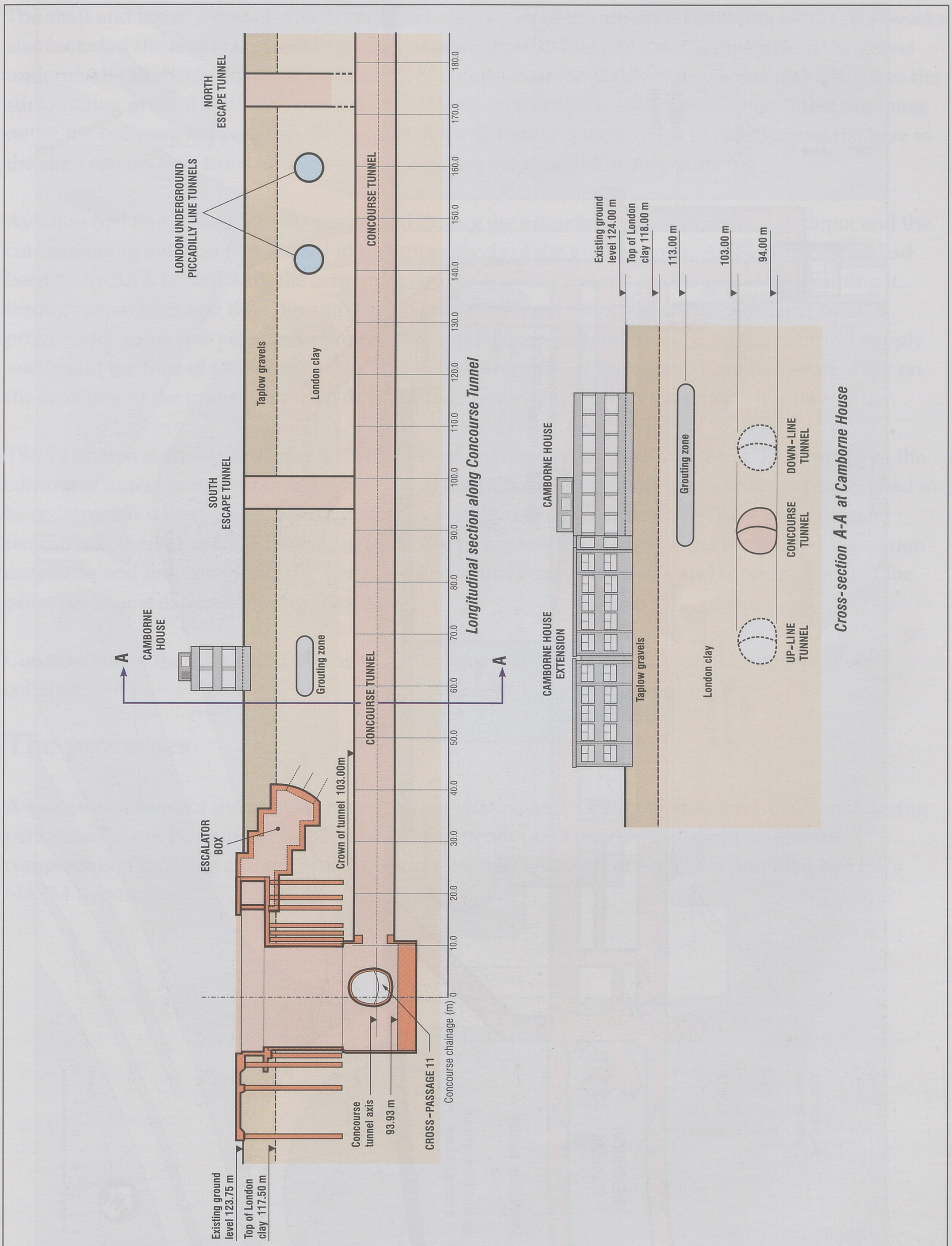


Figure 4 *Cross-sections of the CTA tunnels*

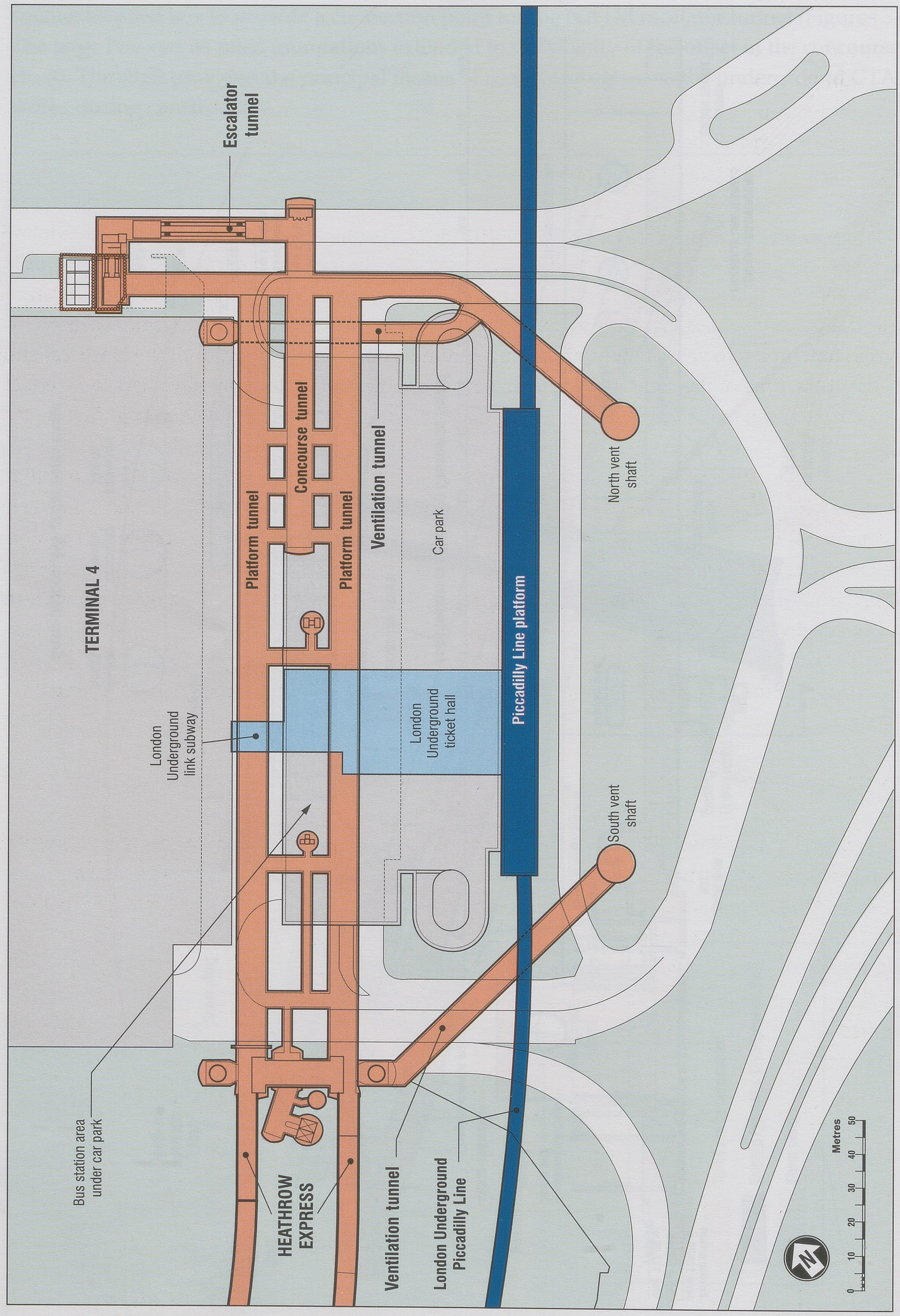


Figure 5 *Layout at Terminal 4*

30 The shaft and boxes were separately constructed as a part of the advanced enabling works. The works also included the removal of some redundant underground fuel tanks and a pipe jack in the gravel underneath Camborne House. Construction of a large shaft inevitably causes some disturbance to the surrounding ground and this can weaken it. However, there is no evidence to suggest that anything out of the ordinary happened in this respect, notwithstanding some delay in constructing the base to the shaft caused by a truck falling into the shaft (see paragraph 6 of Appendix 6).

31 Aviation fuel had leaked into the gravel bed during the extended operation of the fuel depot and the contaminating aviation fuel floated in the upper levels of the groundwater. An earlier contract had been let by BAA to deal with the contamination by drawing water from the gravel bed, putting it through separators and then returning the cleansed water to the ground. This work had been in progress for some two years before tunnelling commenced and continued until the electrical supply was lost at the time of the collapse. The long-term movement of water may have had some effect on the structure of the gravel bed but it did not affect tunnelling work in the underlying clay.

32 The T4 Station is shown in Figure 5. The platform layout was broadly similar to CTA except that the concourse tunnel was substantially shorter and the tunnels were more closely spaced. Tunnels had to be constructed wholly under areas open to the public, including the terminal's car park, bus and pedestrian circulation areas. The tunnels were to pass a few metres below the Piccadilly Line station concourse and link corridor to T4. The north and south ventilation shafts and tunnels provided the principal means of access during construction.

33 Construction of the CTA and T4 stations created obvious hazards to the public in the event of collapse.

The processes

34 A synopsis of some of the more important issues concerning NATM, including means of monitoring performance, can be found at Appendix 1. The appendix also provides information about compensation grouting and the ground. A comprehensive review of NATM is provided by HSE's NATM Report.[1]

The trial tunnel and subsequent preconstruction developments

The trial tunnel

35 A trial tunnel consisting of a single-platform-sized NATM tunnel some 100 m long was successfully formed from the car park 5 shaft (see Figure 1). Three different tunnelling sequences were tried. First two temporary internal walls were used and then, successively, one and none. The tunnel was subsequently lined during the main construction works some two years later to form a part of the running tunnel towards T4.

36 The trial tunnel was designed and its construction overseen by a specialist consultant, The Dr Sauer Company, engaged at BAA's request by the lead designers, Mott MacDonald. Taylor Woodrow acted as BAA's construction managers and closely supervised the trial tunnel contractor who was not involved in the subsequent construction work.

37 There were a number of differences between construction work at the trial tunnel and the full project:

- the method of supervision differed;
- there was no compensation grouting;
- construction involved a single rather than a triple tunnel system;
- the NATM designer was integrated into the client's design and supervisory team;
- piezometers (see Glossary, Appendix 8) were used as a part of the monitoring instrumentation; and
- the detailed design included lattice girders around the full tunnel section where the work sequences were similar to those later adopted at the full project. (Fully circumferential ribs were not used in one section of the trial tunnel - that with no temporary internal wall - where their use was impractical due to the excavation sequence adopted for the invert.)

Post-trial developments

38 Discussions then followed between the client and their advisers about the most appropriate way to carry forward the use of NATM and to deal with settlement control.

39 A decision was taken by BAA that the primary NATM tunnel linings should be for the contractor to design as 'temporary works'. BAA subsequently provided data from the trial tunnel to the tendering contractors but did not restrict them to NATM. A NATM performance specification was developed, essentially requiring the formation of voids within which the client's permanent works, *in situ* concrete tunnels (the secondary linings), could be constructed. Partially completed NATM design work earlier undertaken for BAA by The Dr Sauer Company for the CTA and T4 stations was shelved.

40 In essence, BAA decided that NATM works should be procured on a 'design and construct' basis rather than by the more traditional route whereby a client's engineer develops a design and exercises supervisory oversight during construction. The contractor's design team was solely responsible for the 'primary' NATM linings. Mott MacDonald retained responsibility for the design of the client's secondary linings.

41 BAA opted for an approach using performance specifications for the control of settlement brought about by tunnelling. Limits were variously set for angular distortion and for total settlement of particular structures and other infrastructure. Subject to the contract, damage caused by settlement beyond the set limits was to be remedied at the contractor's expense. Contractors were free to choose the settlement control measures. However, the client had presumed that the perceived cost advantages of compensation grouting would exclude other alternatives and had reserved areas from where it could be carried out.

42 The adoption of performance specifications meant that the commercial and technical risks of NATM and compensation grouting passed to prospective contractors. They had to weigh up these risks in the competitive tendering process and carry out the work to their own designs and specifications. The use of performance specifications meant that BAA's supervisory team was less able to intervene during design and construction of the NATM works.

43 A new and innovative form of construction contract, the New Engineering Contract, was selected by BAA. This was its first use on a major tunnelling project. As a consequence, parties had to understand their contractual responsibilities and learn how to manage their activities and communications under an unfamiliar set of rules at the same time as using technologies unfamiliar to London clay.

44 'Self-certification' of quality was suggested to BAA and was introduced into the contract. This was a major departure from the more traditional approach where close scrutiny by an independent team is provided to secure the client's interests. Thus, self-certification further limited close supervision by the client team and placed a greater onus on the contractor to complete the work satisfactorily. BAA chose to confine its role to auditing the contractor's self-certification scheme. The contractor had to devise systems, including training, to deal with new ways of working. This was to prove difficult, especially in the early stages of the work.

45 The New Engineering Contract linked payment to the satisfactory completion of activities, for example a length of platform tunnel. Any related 'defect' notices from the self-certified quality scheme had to be resolved before payment was made. The contractor's creation of such notices had the potential to delay payment.

46 A project control manual was developed by Taylor Woodrow for BAA. It required the principal contractor to prepare a number of documents for each programmed activity. For NATM these were:

- a quality inspection and test plan;
- a method statement;
- a risk assessment; and
- a NATM support sheet (see paragraph 67).

47 The project was split into a number of packages by BAA. The civil engineering works (excluding any fitting out) south of Shepiston Lane was a single contract. Tenders were invited for this package towards the end of 1993 from six teams that had pre-qualified. All but Balfour Beatty Civil Engineering Ltd (Balfour Beatty) involved joint ventures. Balfour Beatty had previous NATM experience, including their involvement in the Channel Tunnel project.

The tender stage

48 Balfour Beatty made conditional agreements with others during the tender period. These included:

- Geoconsult Ges MBH of Salzburg Austria (later to change name to Geoconsult ZT GMBH) as expert NATM advisers and designers;
- Mott MacDonald to provide settlement predictions and to advise on control measures (this involved BAA's agreement and the establishment of 'Chinese walls' within Mott MacDonald so as to avoid any conflict of interest); and
- Keller Colcrete for compensation grouting.

49 Balfour Beatty's project director advised Geoconsult to keep their tender to the absolute minimum. The need to substantially reduce their tender was stressed during negotiations.

50 BAA assessed the tenders over the 1993 Christmas period. This involved separate consideration of 'commercial' and 'technical' aspects by two teams set up to work in isolation. Balfour Beatty's £57.5 million tender was the lowest. The technical review covered a range of issues, including health and safety. Assessment was based on a review of contractor submissions for a number of specified work activities including NATM. Numerical scores were assigned, weighted and aggregated. The technical review team were not content with the second and third lowest bids. Balfour Beatty's bid was some £ million less than the fourth lowest at this stage. Balfour Beatty's technical performance score was not outstanding. It ranked third on selected technical criteria and sixth on project risk. However, it is probable that the scoring system underestimated the merits of their submission.

51 Discussions took place between BAA and Balfour Beatty and the performance score was revisited. Similar limited consideration was given to other tenderers but their scores were unchanged apart from minor calculating errors. Balfour Beatty's revised technical performance score then ranked first and their overall risk score was then second. These changes can be explained in part by the high contractual risk initially attaching to the use of a single TBM for the running tunnels (increased to tw during negotiations) and by a failure initially to provide project-specific information about health an safety. Following these negotiations, the contract was awarded to Balfour Beatty in the sum of £60.7 million.

The construction phase

52 The contract was awarded to Balfour Beatty on 7 March 1994. They took possession of the CTA site on 9 May 1994. An advanced contract for constructing the fuel depot shaft and related subsurface structures had just finished.

Settlement control

53 Balfour Beatty engaged Mott MacDonald in an advisory role for settlement prediction and control. Balfour Beatty chose to make extensive use of compensation grouting as the principal means of settlement control. Keller Colcrete was subcontracted to install grouting arrays to patterns they predetermined and to inject grout as directed.

NATM consultant

54 Balfour Beatty placed a subcontract with Geoconsult to design the NATM works and to provide on-site technical supervision. Four points are of note and these are discussed in paragraphs 55-59.

55 The first point involves staffing. The subcontract specified the performance to be achieved for the supply of technical supervision to oversee the NATM construction. This included assisting Balfour Beatty in developing production procedures, in setting up and operating the NATM worksites, and monitoring and data interpretation. The contract required Geoconsult to supply a senior NATM engineer but did not specify the total NATM engineering resource that had to be provided to fulfil their contract. As a minimum, Geoconsult suggested an on-site team of one experienced engineer and two foremen, the latter being used towards fulfilling the supervisory and quality control functions in Geoconsult's contract. Balfour Beatty considered it inappropriate to have more than the senior engineer. This minimised cost but had little regard to the demands and pressures that were to be put on the engineer. Geoconsult accepted the limitation to one on-site engineer. There was a small exception: a Geoconsult foreman provided short-term support when it was believed that BAA would cover the cost because of an error in the tender information affecting Shepiston Lane. BAA had specified a limited number of posts whose filling required their prior consent. The post of senior NATM engineer was one such post. A nominee had been suggested by Geoconsult at the time of tender. A less senior engineer was later accepted. The initial nominee became the link between Balfour Beatty and the Austrian-based design team. He occasionally visited site and provided cover during the summer leave of the engineer on site.

56 The second point concerns Geoconsult's obligation to assist in setting up and operating the NATM worksites. While the achievement of quality during construction was the responsibility of Balfour Beatty, the issue should have been a matter of particular importance to Geoconsult. They raised no objections to the systems proposed by Balfour Beatty. These systems gave responsibility to the production teams to self-certify their work. The procedures for correcting errors were cumbersome. Self-certification could have been adopted without compromising safety, had better systems been proposed. However, it took until mid-September 1994 before a NATM quality system with reasonable prospects of success was established.

57 The third point concerns the striking out of Geoconsult's obligation to supply computer software for handling tunnel monitoring data. Instead, Balfour Beatty chose to provide it. Geoconsult's site engineer was not impressed by the system selected. Considerable time was lost in manipulating data before outputs could be obtained and Balfour Beatty's survey methods sometimes caused variable data accuracy. In July, and again in September, Geoconsult's site engineer wrote to Balfour Beatty recommending a switch to alternative software and surveying systems. These requests were rejected. Despite the pressures under which their engineer was working, Geoconsult did not ease them by introducing a second engineer or by insisting on better software. There was an increased likelihood of mistakes as a consequence. However, the unsatisfactory software did not significantly affect the ability to identify and interpret key events that were later to become crucial. Moreover, the raw data were readily usable in any specific engineering assessment that was reasonably called for in the circumstances.

58 The fourth point concerns Geoconsult's quality assurance manual. This required their site engineer to certify that the NATM linings had been constructed in accordance with Geoconsult's designs. The manual required Balfour Beatty similarly to certify.

59 Geoconsult's site engineer reported to Balfour Beatty's engineering manager and was, to a degree, integrated within Balfour Beatty's engineering team. Geoconsult's site engineer was not involved in all the engineering meetings held between Balfour Beatty and BAA, and was not on BAA's circulation list for papers. Balfour Beatty directly employed three junior engineers to work under the control of Geoconsult's site engineer. The three were called 'NATM engineers'. However, they had limited experience of tunnelling and no experience of NATM in soft ground. Their role was intentionally restricted. They were responsible solely for installing and reading some of the monitoring instruments. Although the duties of the three 'NATM engineers' did not extend to the quality of construction, they did, in the event, bring about some key changes to quality assurance procedures. A fourth junior engineer was added at the end of August 1994. He had earlier worked for the BAA team and had practical NATM experience, although not in soft ground such as clay. He had a different role and exclusively worked at CTA dealing with quality and production difficulties which, by that time, were well-known to Balfour Beatty and Geoconsult. A team of Balfour Beatty surveyors monitored the in-tunnel pins (or targets) used for monitoring tunnel movements (see Appendix 1). The results were made available to Geoconsult's site engineer on a daily basis and periodically to BAA.

NATM design

60 Geoconsult based their detailed designs on the shapes of the finished tunnels. They were assisted by earlier geological investigations. In 1990, Heathrow Airport Limited had commissioned ground investigations to inform design work. Conventional sampling and testing techniques were used and the investigations were general in nature. Although the use of NATM was under discussion, the ground investigations did not specifically consider the needs of NATM designers. Since the bore holes could not wholly eliminate the possibility of natural features that might have been hazardous for NATM, more should have been done to confirm the ground properties needed for ground modelling as a part of the NATM design.

61 Geoconsult prepared a detailed design using the data that were available and the precedence afforded by the trial tunnel. Design data were derived by analytically modelling tunnel behaviour using finite-element analysis. The numerical model used for design was not correctly calibrated against the results available from the trial tunnel. Compensation grouting was not formally included in the calculations undertaken to predict the loads in the lining. It is good practice to validate computer software in accordance with the National Agency for Finite Element Methods and Standards (NAFEMS),[3] and the Association of Geotechnical Specialists.[4] However, this was not done. At the time, such omissions were common practice. The failure to adequately predict surface settlement from multi-tunnelling activities was to have significant consequences during construction.

62 The client had not specified factors of safety for use in the NATM design. This was left to the contractor. Such factors are used to ensure that design values for imposed loads and material strengths reflect the variability met in practice. Design codes provide such factors for some types of structures but there is no UK code specifically for tunnels. British Standard 8110 Part 1 (as amended) is normally used as a reference.[5] Germany has a similar standard, DIN 1045.[6] The overall factor of safety is arrived at by multiplying the load factor by the material factor. Geoconsult selected their own values. A comparison is as shown in Table 1.

Table 1 *Calculating the overall factor of safety*

Source	*Load factor*	*Material factor (concrete in compression)*	*Overall factor of safety*
BS 8110	1.4	1.5	2.1
DIN 1045	1.75	1.43*	2.5
Geoconsult	1	1.5	1.5

*See DIN 1045, Table 12 and Figure 1.[6]

63 The higher the number, the greater the factor of safety. Geoconsult adopted low values and their NATM lining designs reflected this.

64 Geoconsult's designs used a typical lining thickness of 250 mm, the same as the trial tunnel. The CTA concourse tunnel was locally increased to 300 mm where it was close to the lower end of the escalator tunnel (between ch. 30 and 80) to take account of the increased loads. The platform and

concourse tunnels comprised six elements sequentially constructed in 1 m lengths: the crown, bench and invert of the side gallery and, similarly, of the enlargement (see Figure 6). Forepoling (see Glossary, Appendix 8) was shown on Geoconsult's drawings as a contingency method for poor ground. In the event, it was not used.

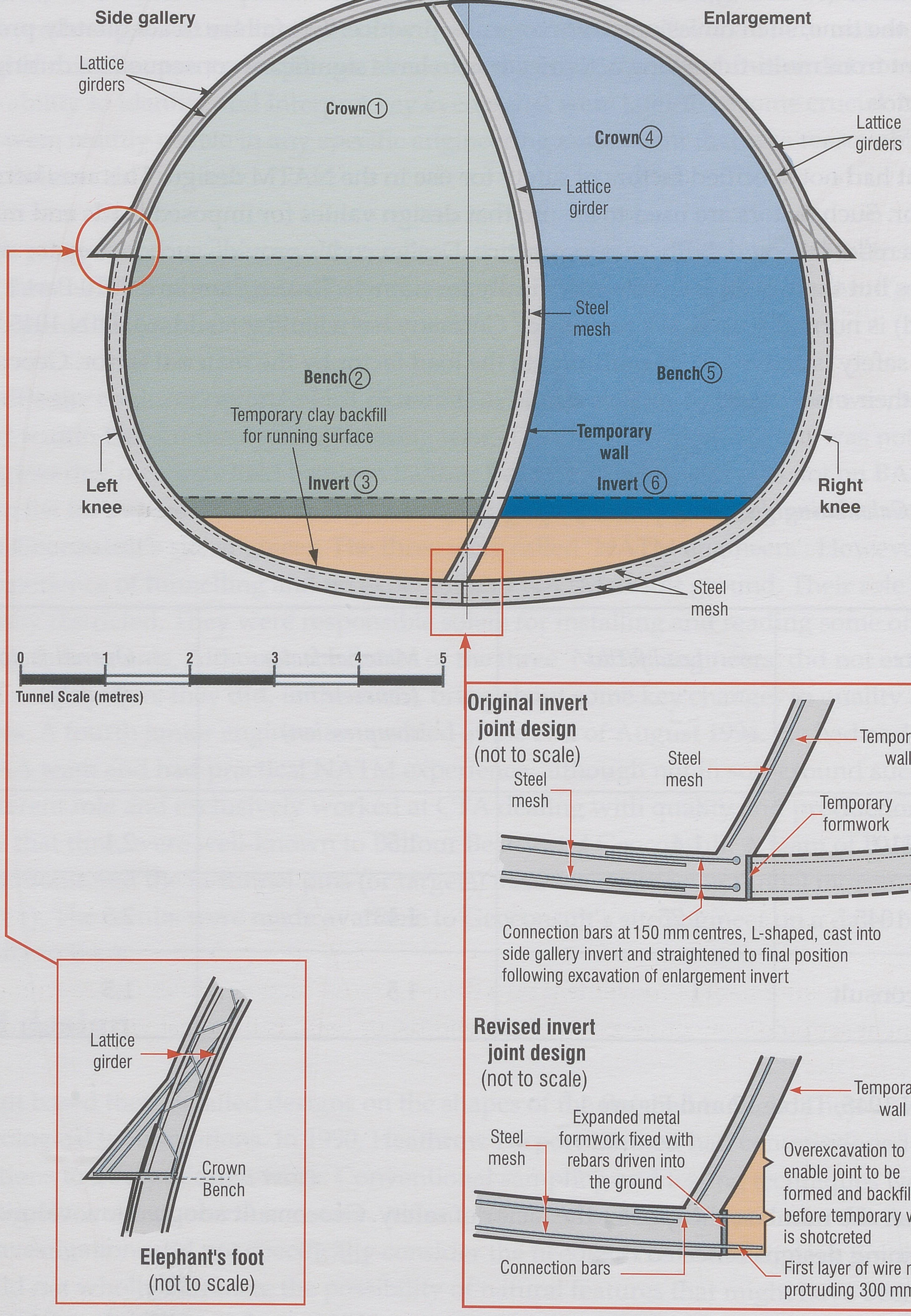


Figure 6 *NATM tunnel and details*

65 The design did not adequately reflect the general lack of NATM experience in London clay or the relative inexperience of Balfour Beatty's workforce. Buildability issues, that is the ease with which something can be correctly built, were not properly addressed. The flattened invert was a case in point. It meant that minor variations in shape could result in major adverse effects on the structural performance of the lining.

66 Rigid lattice girders were specified for the crowns. Their omission from inverts added to difficulties in maintaining the correct profile during excavation and it was less easy to detect insufficiencies in the thickness of the shotcrete. The design of the invert joint (the joint at the foot of the temporary wall) was poor and went through several modifications during the work. Without lattice girders there were no clear points for connecting the enlargement and side gallery inverts. There were risks that these would not align and that the invert would be too thin. There was the added risk of non-continuity in steel reinforcement across the joint, not least because of damage to exposed starter bars and mesh projecting from side gallery inverts caused during excavation for the enlargement inverts.

67 The design was presented in the form of a design brief and included drawings showing geometrical arrangements and dimensions, reinforcement and joint details and construction sequences. Balfour Beatty submitted the designs to BAA. Mott MacDonald carried out some limited reviews, essentially to ensure that the designs were compatible with the permanent works. There were no major points of disagreement. The designs were supplemented by NATM support sheets which were progressively issued during construction and provided detailed instructions, in tabulated form, for short lengths of the tunnels.

68 Although the linings were especially vulnerable from the effects of poor workmanship, they could have been safely constructed. However, the margin for error was small and rigorous inspection and monitoring during construction was necessary.

NATM monitoring

69 Monitoring is vital to determine the behaviour of the lining and ground. Unsatisfactory trends must be identified sufficiently early to enable corrective steps to be taken. Careful consideration has to be given to the number and location of monitoring points. A number of methods can be used. Direct measurement of movement on a tunnel's cross-section (either to determine absolute movement at set points or convergence along chords, or both) is the most vital and provides the most readily interpretable data.

70 People were unaware of the critical failure mechanisms in Geoconsult's design. In particular, the sensitivity of the flattened invert to structural weakness caused by variations in the construction of the invert joint and in profiling the invert was not appreciated. The tunnel instrumentation specified by Geoconsult was inadequate for monitoring crucial movements in the tunnel invert (ie heave in the invert). More generally, predefined trigger levels against which to monitor magnitudes and rates of change were not set by the designer as a part of the design.

71 Monitoring instruments were installed as described in Appendix 1. Figures 7 and 8 show how the

information from monitoring targets within the tunnels was displayed (colour has been added to assist the reader). Figures 7 and 8 show the same data, displayed in two different forms, for ch. 30 of the CTA concourse tunnel (see Figures 2 and 23 for the location of ch. 30).

72 Figure 7 shows the data as vector plots with an outline of the tunnel and the seven targets uniquely numbered 0031 to 0038 (the identifier 0036 was not used). Movement is shown by the colour-coded lines. The movement plots are to an enlarged scale compared to the tunnel outline. Thus Figure 7 shows that at ch. 30:

- 0032 at the crown had moved mostly downwards and a little towards the centreline;
- 0031, 0033 and 0037 high up on the walls had moved mostly downwards and also inwards;
- 0035, 0034 and 0038, all close to the invert, had moved downwards and significantly inwards;
- 0033 and 0034 were removed when the central wall was demolished; and 0037 and 0038 were lat installed when the enlargement was constructed. Target 0038 was lost and belatedly replaced by 0038A. Hence, an indication of the total movement in the ground close to the bottom right-hand segment of the tunnel is in excess of the addition of 0038 and 0038A as movement will also have occurred in the intervening period when these pins were absent. The total movement was appreciable in this particular case and likely to be similar to target 0035.

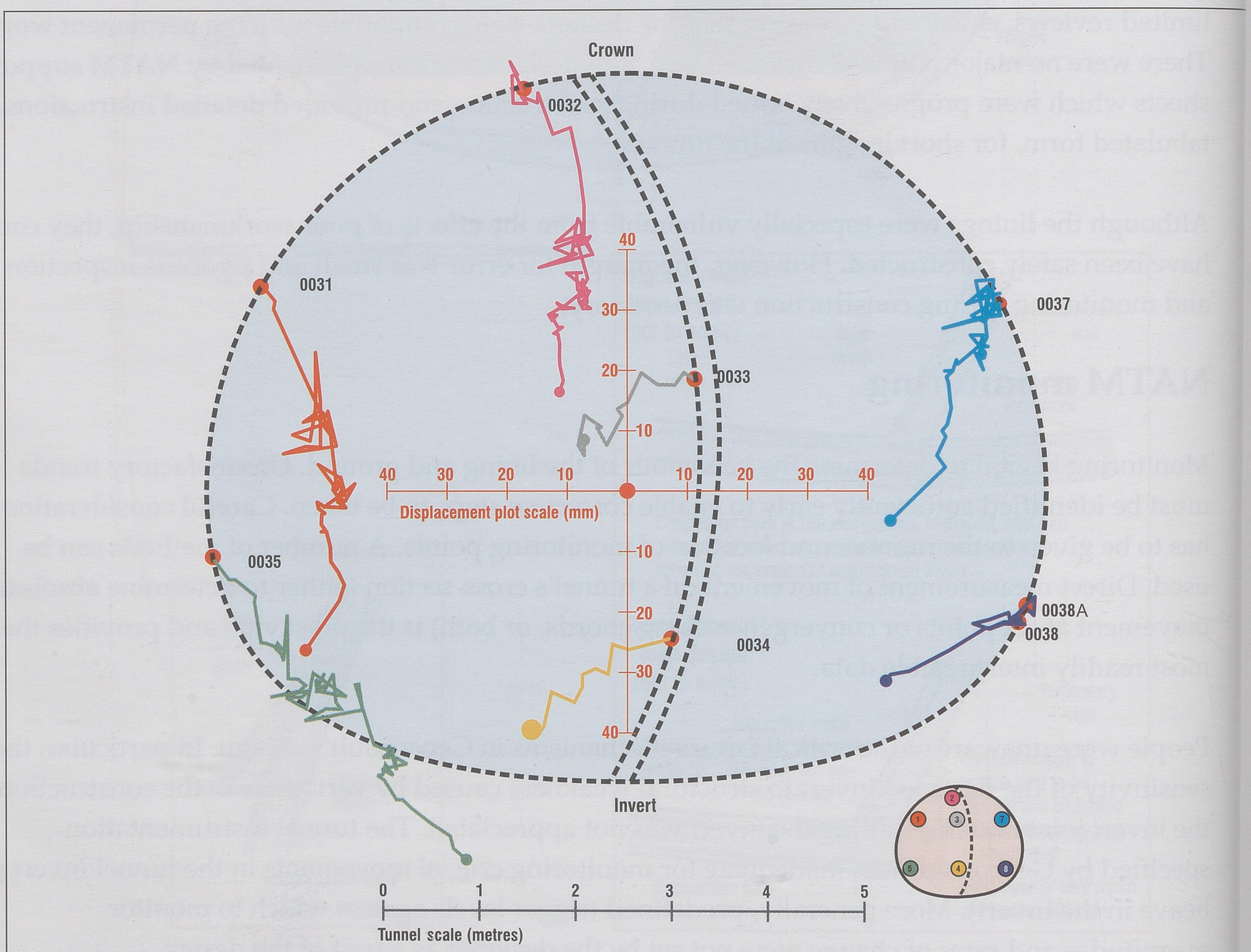


Figure 7 *Vector plots for concourse tunnel, ch. 30*

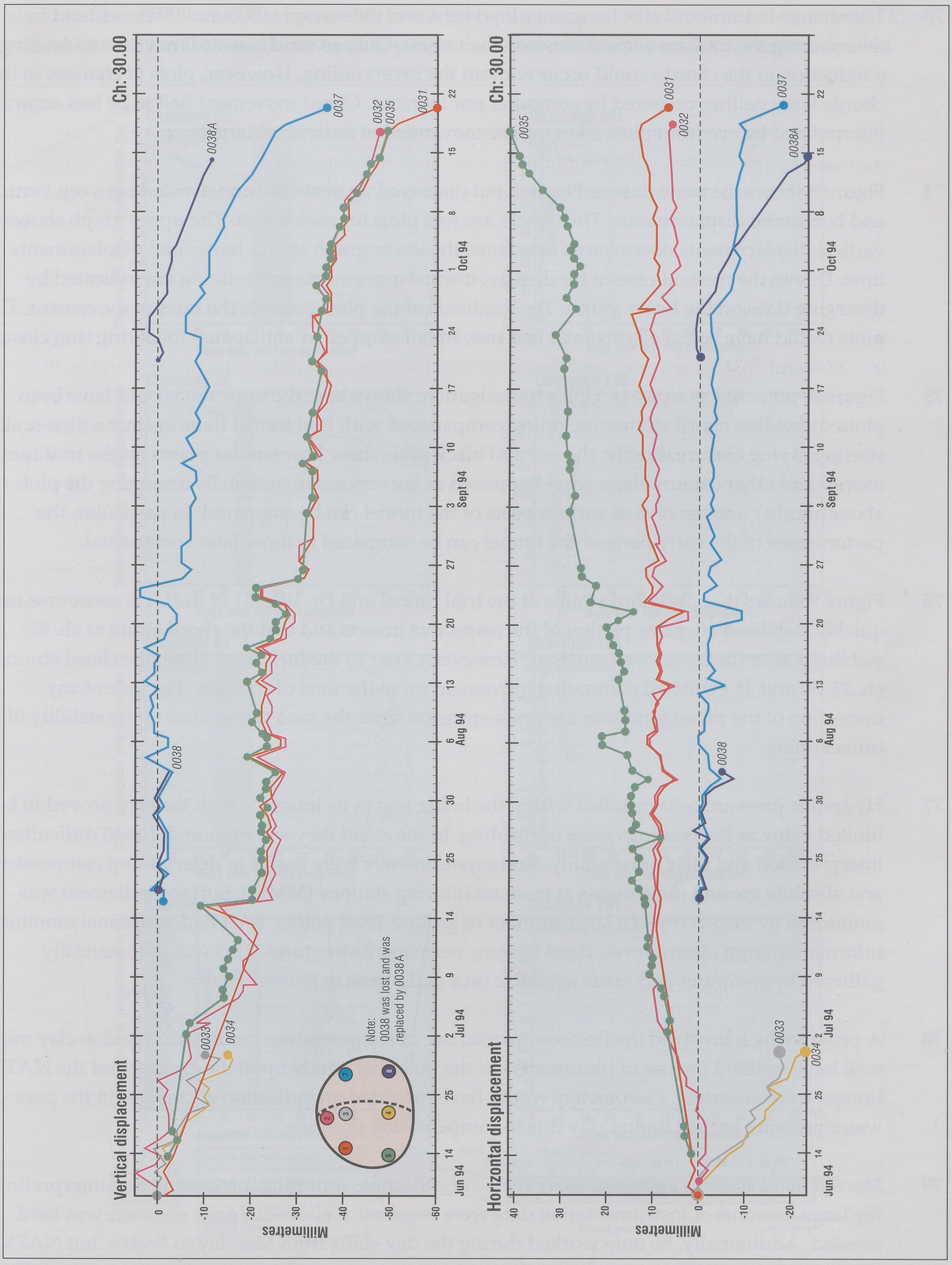


Figure 8 *Displacement plots for concourse tunnel, ch. 30*

73 The change in the chord (the imaginary line) between, for example 0035 and 0038, is found by determining the total movement between the targets. Only so much inward movement - leading to a reduction in the chord - could occur without the invert failing. However, plots of changes in the chords were neither prepared by computer nor by hand. Chord movement had to be less accurately interpolated by eye from plots showing the movement of individual targets.

74 Figure 8 shows the same data as Figure 7 but displayed against time and divided between vertical and horizontal displacements. Thus, there are two plots for each target. The upper graph shows vertical displacements downwards over time; the lower graph shows horizontal displacements over time. Due to the method chosen for display, inward movements in the lining are indicated by diverging lines on the lower graph. The gradients of the plots indicate the rates of movement. The plots would have become horizontal had movement stopped as anticipated following ring closure.

75 Figure 9, prepared as a part of HSE's investigation, shows how the same data could have been plotted showing chord strains, including comparisons with trial tunnel data, against a time-scale starting at ring closure. Briefly, the red and black plots show how similar points on the trial tunnel moved and other colours show what happened at the concourse tunnel. By arranging the plots one above another, movements at various parts of the tunnel can be compared. In particular, the performance of the early parts of the tunnel can be compared to those later constructed.

76 Figure 9 shows that the chord strains at the trial tunnel and ch. 104-151 of the CTA concourse tunnel quickly stabilised after completion of the respective inverts and that the chord strain at ch. 87 stabilised after the invert was repaired. However, closer to the fuel depot shaft, the chord strains for ch. 23, 30 and 41 exhibited continuing movement up to the time of collapse. The lack of any inspection of the invert joint was a serious omission since the joint was critical to the stability of the tunnel lining.

77 Hydraulic pressure cells installed within the lining and at its interface with the clay proved to be of limited value as the readings were misleading. In the event they were ignored due to difficulties in interpretation and their unreliability. Rod extensometers were useful in determining comparative and absolute ground movements at main monitoring stations (MMSs). Surface settlement was monitored by the survey of a large number of ground-level points. BAA had additional monitoring information from electro-levels fixed to some permanent structures. This was automatically gathered by computer and made available on a daily basis to Balfour Beatty.

78 A project which involved the first commercial use of compensation grouting in London clay might well have justified the use of piezometers as the potential effects upon the ground and the NATM linings were uncertain. Piezometers would have provided an indication of changes in the pore water pressure in the London clay due to compensation grouting.

79 Management systems and resources capable of collecting, inputting, processing and interpreting the large amounts of instrumentation data were required. Geoconsult's site engineer was hard pressed. Additionally, he only worked during the day shifts from Monday to Friday; but NATM construction, and the need for expert support, went on around the clock, seven days a week. There were extended periods, particularly at weekends, when no expert assistance was available. His

workload increased when the project fell behind programme as additional tunnels were started to try and make up time. It should have been apparent that Geoconsult's site engineer was overloaded.

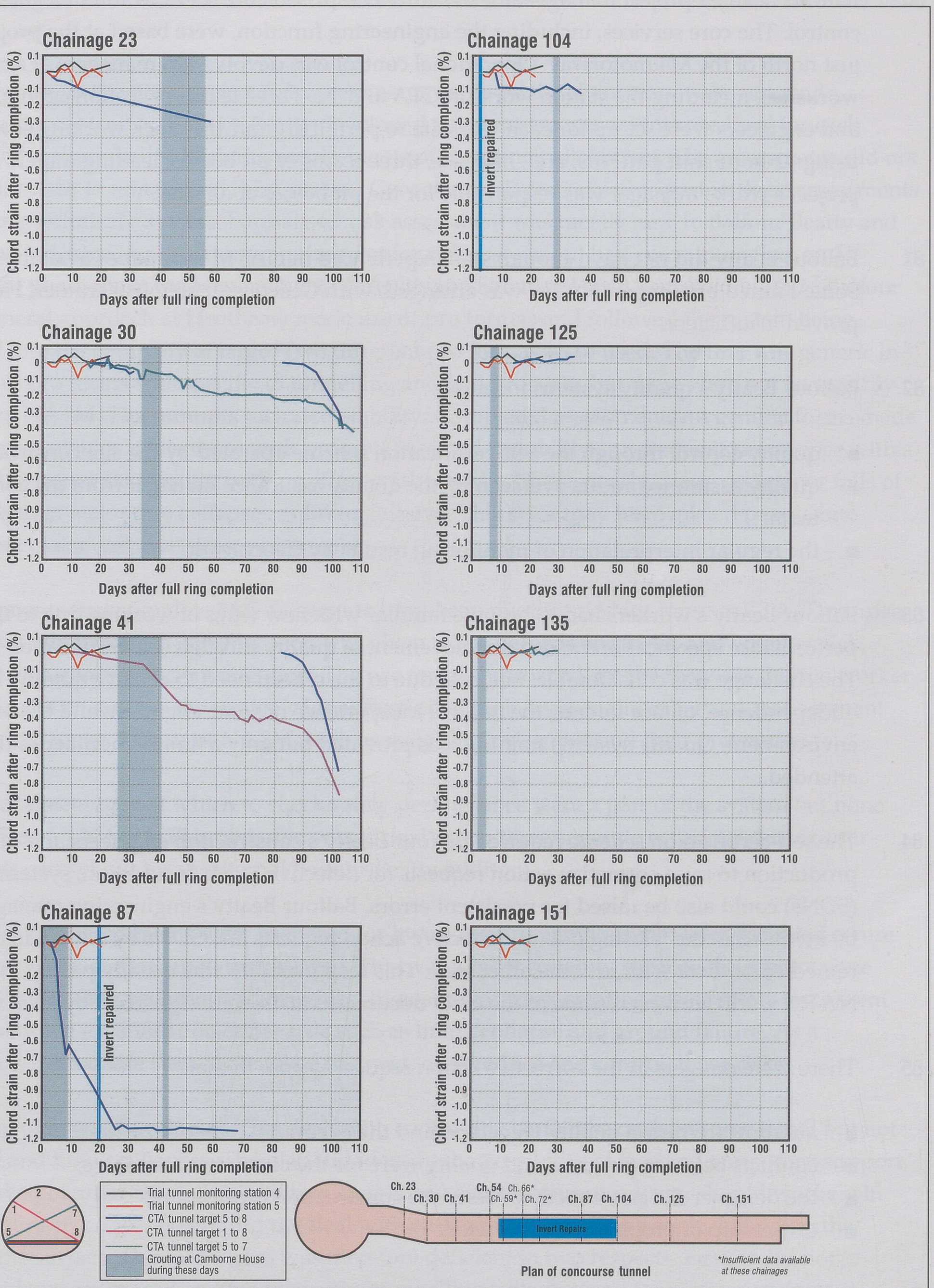


Figure 9 *Chord strains across inverts of the trial and concourse tunnels*

Construction management organisation

80 Balfour Beatty's project management structure comprised core services and delegated local operati control. The core services, including the engineering function, were based at the project's main offic just north of the M4 motorway. Operational control was devolved to managers at a number of worksites, including the station works at CTA and T4. Three teams of section agents, section engine and engineers were set up for each worksite to permit around-the-clock working seven days a week using 12-hour shift patterns; and, likewise, three teams of pit bosses, leading miners and miners. Th project's works manager was responsible for the pit bosses at all sites.

81 Balfour Beatty did not have enough staff experienced in NATM techniques available for the project Some limited briefing on NATM was arranged, with Geoconsult acting as trainer. However, this proved insufficient.

82 Balfour Beatty's quality systems included:

- quality control through the self-certification scheme operated by the site construction teams;
- quality assurance audits overseen by the quality assurance manager from the core engineering team;
- the regular interpretation of monitoring results by Geoconsult.

83 Balfour Beatty's workers had to become familiar with new ways of working due to the use of performance specifications and the achievement of quality through self-certification and auditing. The challenge was considerable, not least due to the crucial need to achieve quality, the traditional 'independence' of face miners, the relative inexperience of some engineers and the working environment. Quality systems training was provided but only a limited number of those at the CTA attended.

84 The self-certification scheme required Balfour Beatty's construction engineers and others involved i production to raise corrective action requests for defective work. In addition, system defect notices (SDNs) could also be raised for persistent errors. Balfour Beatty's engineering manager had to be involved in the 'closing out' of corrective action requests and SDNs by which defects were either remedied or dealt with in some other way. This responsibility was usually passed to Geoconsult for NATM work. However, some of the early documents at T4 were signed off by local site staff.

85 There were dangers in the corrective action request system in that:

- attempts to control quality lagged behind the event;
- conflicts between progress and quality were for the contractor to resolve;
- the designer did not directly oversee the construction process; and
- ownership of problems was diffused.

86 Balfour Beatty had closely defined company safety procedures. Responsibility for health and safety the project was delegated to agents at the various worksites. They made weekly site inspections wit pro forma reporting such that safety could be discussed as necessary at weekly management meeti

87 A site safety manager was responsible for advising the agents and for monitoring their safety performance. He carried out, by invitation and by his own volition, safety inspections including some 24 instances where written reports were subsequently prepared. None related to the safety of NATM.

88 As was common at the time, project risk assessments made by the client team were not made available to the contractor. Balfour Beatty developed risk assessments at worksite level for each programmed activity in line with the requirements of the principal contract. The assessments did not fully identify risks to miners and third parties. Geoconsult played no active part in these assessments despite being technical advisers. Formalised risk assessment was mostly new to Balfour Beatty and others in the industry. A regulatory requirement for risk assessment had come into effect on 1 January 1993 pursuant to the Management of Health and Safety at Work Regulations 1992.[7] Balfour Beatty's general approach at Heathrow made use of pro formas and followed the system being introduced into the company at large. Two different pro formas were used. The first was generic in form. A later pro forma was specific to tunnelling and had prompts, but these were not necessarily particular to NATM. The prompts included stability. Completed assessments on generic forms made no mention of collapse while those with prompts assessed instability as a frequent occurrence with a probability of minor injuries but with no effect on the public. These clearly concerned minor falls of earth rather than major face collapses or lining failures. This error may have misled people into thinking that major collapses were not possible.

89 Risk assessments first completed for T4 seem to have been photocopied for reuse at CTA. This raises doubts about whether fresh consideration was given to the hazards and risks, and whether risk assessment was given sufficient attention. The pro forma approach kept the focus on routine worker safety. It did not encourage the strategic identification of high-level engineering and management issues essential to the success of NATM, such as major hazard events and their prevention.

90 Field control sheets against which to check safety performance were a part of the system but none were prepared for NATM. This omission was picked up on three separate occasions during four safety audits carried out by an external Balfour Beatty auditor.

91 Crucially, no risk assessments were prepared for invert repairs, activities that later occupied centre stage in the events leading up to the collapse. This was almost certainly because the repairs were unplanned rather than programmed activities. It meant that work creating major safety risks went ahead without the identification of hazards such as lining collapse and ground failure. As a consequence, inadequate steps were taken to avoid, or to reduce and control, these risks.

92 A site safety plan was developed. This dealt with controlling certain hazards in some detail but not tunnel face and lining collapses. The plan did identify the possibility of face and temporary support failure as two potential causes for initiating emergency evacuation procedures, should workers in the tunnel be at risk. However, it did not deal with emergencies affecting people, including the public, on the surface. The safety plan was therefore deficient in two respects. First, it did not provide guidance on procedures for preventing tunnelling collapses and for recovering from developing adverse events, and, second, it did not fully deal with emergencies. This was unsatisfactory.

Developments affecting the BAA site supervisory team

93 BAA and Taylor Woodrow agreed to amend the contract between them at about the time Balfour Beatty started work on site. A reduction in the number of packages to be managed had reduced the span of Taylor Woodrow's control and a narrow line of command went from BAA's team through Taylor Woodrow's to the construction contractors. BAA believed there was unnecessary duplication and that it was becoming increasingly difficult to differentiate between the functions of the BAA and Taylor Woodrow teams.

94 Although Taylor Woodrow ceased to be project manager, most of their staff were seconded to BAA and worked under its control and direction as a part of the client's team. The client's project control plan was not amended to show the new management arrangements until after the collapse. It is doubtful that the timing of this reorganisation, coinciding with Balfour Beatty's start on site, was helpful.

95 BAA divided the project into a number of areas for the purposes of local management. The stations CTA and T4 were two of these. This broadly mirrored the contractor's organisation. Core services were located next to Balfour Beatty's and staff were also based at the various worksites. Staffing was substantially reduced during night shifts. The CTA area manager had been involved from the early stages of the project and had developed the project control plan. Working under him was the CTA construction superintendent, an experienced tunnelling engineer, but he did not take up post until early July 1994 when tunnelling had been under way for some weeks.

96 BAA's safety management arrangements involved a number of disparate strands. Shift engineers within the area management structures carried the front-line health and safety role as a part of the area managers' safety responsibilities. Monthly safety audits involving the review of selected activities were planned but proved too ambitious and there was a shortfall in the number carried out. CTA NATM excavation was never audited.

97 A BAA project safety adviser fulfilled a central advisory role. He took a 'hands-on' approach, spending much of his time carrying out site visits, dealing directly with Balfour Beatty's agents through joint weekly tours, and checking method statements and major plant items. NATM design and construction quality were not within his remit. Monthly high-level safety meetings formed a part of BAA's strategy but were only held in the two months before the collapse. BAA's project safety adviser had little contact with Balfour Beatty's on-site safety manager.

98 BAA additionally engaged a part-time safety consultant. He acted as an adviser to the project manager, provided training for the BAA team and played a part in developing induction videos. He worked independently of the project safety adviser. The consultant was asked in December 1993 to review existing safety systems. He reported in March 1994, advising that the current system was too closely modelled on a contractor's system rather than taking a client's viewpoint. Between April and June 1994 a 'safety vision' initiative was developed involving the expression of strategic safety goals. It was launched in September 1994 when directors of BAA and principal contractors were present: little more was effectively done before the collapse.

99 The failure to amend the project control plan to reflect BAA's new management arrangements created difficulties for their site supervisors and compounded the general uncertainty regarding self-certification and auditing. This was unhelpful. These matters remained unresolved, although they received a major airing on 13 October 1994, just one week before the collapse, when BAA's senior project manager met representatives from across the team.

100 Senior BAA managers came under considerable pressure soon after construction started to reduce planned supervisory resources. This absorbed senior managers' time, but had little practical effect before the collapse.

101 There were insufficient resources for BAA to carry out the auditing programme they had planned. The BAA team was further hampered by the lack of a quality manager until July 1994. Until then there was no one to liaise with Balfour Beatty's quality control manager nor to manage BAA's audit process. Those audits that were completed led to complaints from Balfour Beatty site staff that they were overly bureaucratic and time-wasting. Planned auditing was reduced contrary to the views of some managers in the BAA team and it remained of limited usefulness. There were no BAA audits of the full NATM process. BAA's T4 team subsequently developed a more direct approach to the NATM work. They used check sheets just prior to shotcreting. This was at a critical time in the production cycle as potential defects could be seen and corrected. BAA's CTA team also changed their approach and began intervening on issues causing concern.

102 The proposed Construction (Design and Management) Regulations (CDM),[8] which were enacted in 1994 and came progressively into effect from March 1995 (ie after the collapse), were a live issue during the development of the project and BAA endeavoured to pre-empt some aspects. The Taylor Woodrow project management team had drawn up the project control plan with this in mind and gave to themselves the pivotal role of planning supervisor. Eighteen major tasks were assigned to the role by the project control plan although a number of these would not have been for a planning supervisor had CDM then been in force. However, only one task, concerning a small part of the health and safety file, was carried forward following BAA's reorganisation. None of the proactive functions concerning the design process and the co-ordination of design work took place. This was unfortunate given the issues surrounding NATM and the desirability for close co-ordination between the design of the temporary and permanent work (see the NATM Report[1]). However, it should be noted that the transitional provisions of CDM had yet to bring client and planning supervisor duties into play.

The start of CTA tunnelling

103 Balfour Beatty began constructing the first major NATM tunnel, the CTA concourse tunnel, on 27 May 1994, 18 days after taking possession of the site. They broke out from the fuel depot shaft through a 'soft eye' in the wall. The eye was relatively small and this caused some difficulties and delay. At T4, work started on the two ventilation shafts and the tunnels which passed under the Piccadilly Line. Quality was a problem from the beginning.

104 Balfour Beatty had intended to erect and use two batching (ie concrete mixing) plants, one at CTA and one at T4, to provide shotcrete. However, they perceived problems at CTA due to:

- an oversailing tower crane operating on an adjacent site;
- the possibility that it might not be safe to drive lorries over some remaining underground storage tanks.

This delayed the erection of the batching plant and shotcrete was transported by road to CTA from the T4 batcher as an interim measure. Although water required to start the cement's hydration was only intended to be added just before use, the inevitable presence of water in the sand and excessively wet aggregates meant that some initial set was bound to occur during transportation and while the shotcrete awaited use at site. It is apparent from samples later recovered following the collapse that a substantial amount of the shotcrete was seriously understrength. Supply from T4 may well have been a contributory factor. Some loads were rejected and the delay in resupply led to the likelihood of increased ground movement and settlement. There were early problems with the quality of the lattice girders. They were not always formed to the correct profile and this slowed progress.

105 The self-certification scheme failed to deliver the required quality due to the way it was designed and used. The BAA team flagged up general concerns with Balfour Beatty about self-certification as early as 20 July 1994. The response time to corrective action requests was generally too slow for NATM construction. By the time a corrective action request with a suggested remedy had been raised by the site production team and then passed to the engineering team and designer for approval, construction had advanced. This meant that it was necessary to cut out completed lining to effect repairs, so delaying further progress by restricting access to the face and temporarily subjecting adjacent parts of the lining to increased stress. The decision was generally taken to leave the defect unremedied and strive for better build quality in future. This was criticised by Geoconsult's site engineer.

106 Control of NATM work was by means of 'as-built' sheets. These recorded how work had been completed. They did not act as a ready means for conducting checks at critical times during panel construction, in particular immediately prior to spraying shotcrete when there was still the opportunity to correct deficiencies. This was indicative of failures in analysing and understanding the needs of the work.

107 SDNs should have been created by those running the quality system (ie the people doing the work) where repetitive defects occurred and when systems failures were identified during Balfour Beatty's audits. This did not happen in practice. The first SDN on 2 August 1994 came about when a Balfour Beatty 'NATM engineer', frustrated with continuing construction defects, went to the quality control manager. An improved 'as-built' NATM record sheet was introduced; but it failed wholly to resolve the problem. The second SDN was raised on 16 September 1994 after the BAA team had threatened to issue their own SDN. A more suitable pre-shotcreting check sheet was introduced. However, this was 14 weeks after the start of the CTA concourse tunnel. A substantial section had already been constructed to an unsatisfactory standard; this was later to play a significant part in the collapse.

Early problems with the concourse tunnel

108 Progress fell significantly behind schedule, so increasing production pressures. The lack of experienced operatives, supervisors, engineers and managers, the newly adopted quality systems and the lack of direct independent oversight by the client contributed to early quality problems. Better

planning and preparation would have paid substantial dividends. Instead, people had to learn on the job and new management systems had to be tested as work proceeded. These all contributed to an increased likelihood of error. There was an extended learning curve. The formation of the temporary central wall and joints in the lining caused particular problems.

109 Correctly profiling the temporary central wall was difficult. While the profile of crown sections could be checked against the lattice girders incorporated into those panels, the absence of lattice girders in the remainder of the lining meant that bench and invert panels had to be profiled by other means. Methods using string lines, lasers and occasionally profile boards were tried but with limited success. A poorly profiled temporary central wall had an adverse effect when trying to position and shape the invert joint. Proposals originating from site for extending the lattice girders into the bench panels were rejected by Balfour Beatty.

110 The design called for the temporary central wall to be demolished as the last step in constructing an incremental advance of the tunnel. However, the shape of the wall at its point of connection with the crown restricted working space in the crown enlargement during excavation, installation of the lattice girders and shotcreting. A more satisfactory design solution had been provided at the trial tunnel where the temporary central wall was more perpendicular to the crown. A change initiated at the worksite led to the three-step demolition of the temporary central wall - crown, bench and invert - as elements of the enlargement were progressively formed, so creating more working space.

111 Formation of the enlargement invert proved difficult. Excavation to successfully match the position and shape of the invert already formed in the side gallery was hampered by:

- the need not to disturb the temporary side gallery backfill as this was essential for maintaining vehicular access to the side gallery face; and
- the exposed reinforcement from the side gallery invert.

Various methods were used for constructing the invert joint. The design originally called for the connection bars across the invert to be L-shaped, cast into the side gallery invert and then exposed and straightened when forming the enlargement invert (Figure 6). A change initiated at the worksite led to the adoption of a slotted timber board as formwork and through which two layers of straight connection bars were pushed into the clay. An alternative design was suggested by Geoconsult on 1 September 1994 (Figure 6). This required some overexcavation and expanded metal formwork. It used mesh and bars to provide for continuity in the reinforcement. It also moved the invert joint to a less critical location at the back face of the temporary wall.

112 Repetitive construction defects occurred, particularly in the CTA concourse tunnel which was unsound from the outset. This should have been apparent from the monitoring data available at that time. The data indicated that there was excessive circumferential contraction of the invert.

113 Balfour Beatty and Geoconsult were aware of defective workmanship although the full significance was not appreciated. Build quality issues were recorded in the CTA engineers' shift books and in the 'NATM engineers' log book. BAA's CTA site team had similar reservations and quality was the

subject of correspondence with Balfour Beatty. (Appendix 3 provides a summary of major cracking problems at the station complexes.)

114 On 15 July 1994 Geoconsult's site engineer wrote to Balfour Beatty's engineering manager about poo workmanship and productivity. He noted that CTA quality was lower than that of T4 and that, after showing some improvement, it had deteriorated over recent weeks. He:

- noted that excavation of the face was inaccurate (other than in the crown where lattice girders were present) and that work did not follow the specified sequence;
- identified that shotcrete quality was impaired by the delays between batching at T4 and use at CTA;
- adversely commented on the application of the shotcrete, citing:
  - spraying at oblique angles to the face (rather than at right angles) and from too great a distance, leading to poor compaction and distinctive layering; and
  - spraying that commenced in the middle of panels, so increasing the likelihood of rebound in the lower regions of the panels;
- identified that construction joints were becoming points of weakness due to:
  - insufficient overlap of the wire mesh at joints between the crown and bench, and the bench and invert;
  - the damage to, or removal during excavation of, the exposed wire mesh that projected from completed panels and which was intended to provide continuity in the lining's reinforcement;
  - the incorporation of rebound into bench panels due to a failure to remove it from the bottoms of crown panels; and
  - forming the joints with tapered edges rather than right angles;
- adversely commented on the varying experience of the miners and engineers, and the failure to recognise the importance of quality;
- noted that investigation of a 12 m horizontal crack in the temporary wall on 14 July 1994 had found that:
  - the wall had an irregular shape;
  - the shotcrete was insufficiently thick and insufficiently compacted;
  - joints were not at right angles;
  - rebound was present in construction joints;
  - mesh was not sufficiently overlapped; and
  - the shotcrete was of poor quality.

115 Recommendations were made for improving:

- the preparation of joints;
- shotcreting, including by further operator training;
- setting out, including the use of templates;
- supervision; and
- bringing the CTA batcher into use.

116 Further recommendations were made by Geoconsult on 21 July 1994 for faster ring closure to limit surface settlement. Better co-ordination of the construction cycle was suggested, as was a reorganisation to achieve speedier data processing.

117 The potential consequences of the lining defects were as follows:

- Poor control over the shape of the temporary central wall, and the crown and invert joints, created instability of the wall and a weakened lining through the inclusion of points of weakness and stress raisers.
- Poorly formed construction joints with faces not at right angles and the incorporation of rebound material reduced the ability of the structure to support the applied loadings.
- Poor strength shotcrete and underthick linings reduced the ability of the structure to support the applied loadings.
- Insufficiently compacted shotcrete reduced the strength of the concrete and the ability of the lining to carry load.
- Lack of mesh and starter bars at joints reduced the ability of the joint to transmit shear and bending forces.
- Omission and damage to in-tunnel monitoring targets limited effective monitoring of the lining.

118 The engineering design manager in the client's team expressed some early concern about continuing creep across the invert but this was not accepted by the contractor.

Problems under Camborne House

119 The CTA construction sequence required the concourse tunnel to be advanced first, followed by the up-line platform and then the down-line platform. In the first half of July 1994 both faces of the concourse tunnel (ie side gallery and enlargement) passed beneath Camborne House. The building settled more than the 9 mm predicted by Geoconsult from their finite-element analysis work. Balfour Beatty advised BAA that settlement had reached 22 mm and was increasing. The maximum settlement acceptable under the contract was 25 mm. Balfour Beatty pointed out that some settlement had apparently occurred before tunnelling had started and said that this was due to activities outside their control, ie contamination de-watering, the proximity to the fuel depot shaft, and delays in delivering shotcrete. Balfour Beatty was unprepared for countermeasures. Compensation grouting, the means chosen to limit settlement, had been considered necessary only to counter the effects of the second and subsequent tunnels. Hence, compensation grouting equipment had not been installed and compensation grouting had not been undertaken during tunnelling for the concourse tunnel.

120 Although there had been general acceptance of the final ground settlement prediction after all tunnels had been constructed, the intermediate figure of 9 mm following the construction of one tunnel was queried. On 22 July 1994 BAA raised the matter with Balfour Beatty. Settlement at the single trial tunnel had been in the range 25-35 mm. On 3 August 1994 Geoconsult completed a review of their finite-element analysis. Their computer modelling had been unable to predict the 29 mm of settlement which had by then occurred at the CTA. They concluded that the ground had been disturbed.

121 The reliance placed on the 9 mm settlement prediction meant that Camborne House had not been

protected from the risk of structural damage. Balfour Beatty had a choice. They could take no further action and risk the need for remedial works; or they could, at this late stage in the tunnelling process install the compensation grouting equipment and use it to inject relatively large volumes of grout at high pressure into the ground beneath Camborne House. This report describes this form of grouting as 'grout jacking'. The effect of grout jacking would be to lift the structure but it might also have been expected to put considerable forces into the ground. These forces, and their potential effects on the tunnels, were not sufficiently understood. Balfour Beatty's engineer overseeing the compensation grouting had no previous experience of the process. No formal liaison or engineering controls were established between the NATM monitoring and the grouting teams.

122 Action was taken quickly to install grouting tubes under Camborne House and grout jacking began on 5 August 1994 with early positive results shown by a reversal in settlement trends. However, it was not noticed that tunnel monitoring data indicated an immediate detrimental response with significant increases in both vertical and lateral movements at ch. 30, 41, 54 and 72 (Figures 9-11). This suggested that forces due to grout jacking were causing excessive lining movements.

123 Between 9 and 15 August 1994, further grouting was carried out in two passes. This brought the total injection to 29 770 litres, a very large quantity in the circumstances. Surface monitoring indicated a gradual response, with peak heave on 14 August. The southern corner of Camborne House returned to its original level although the north and north-west corners only recovered by some 30%. The strain induced into the ground had acted upwards to lift Camborne House and equally downwards onto the concourse tunnel. This effect was neither anticipated nor considered before grouting began. No special arrangements had been made for additional monitoring and problems were not identified by reference to the data from the instrumentation.

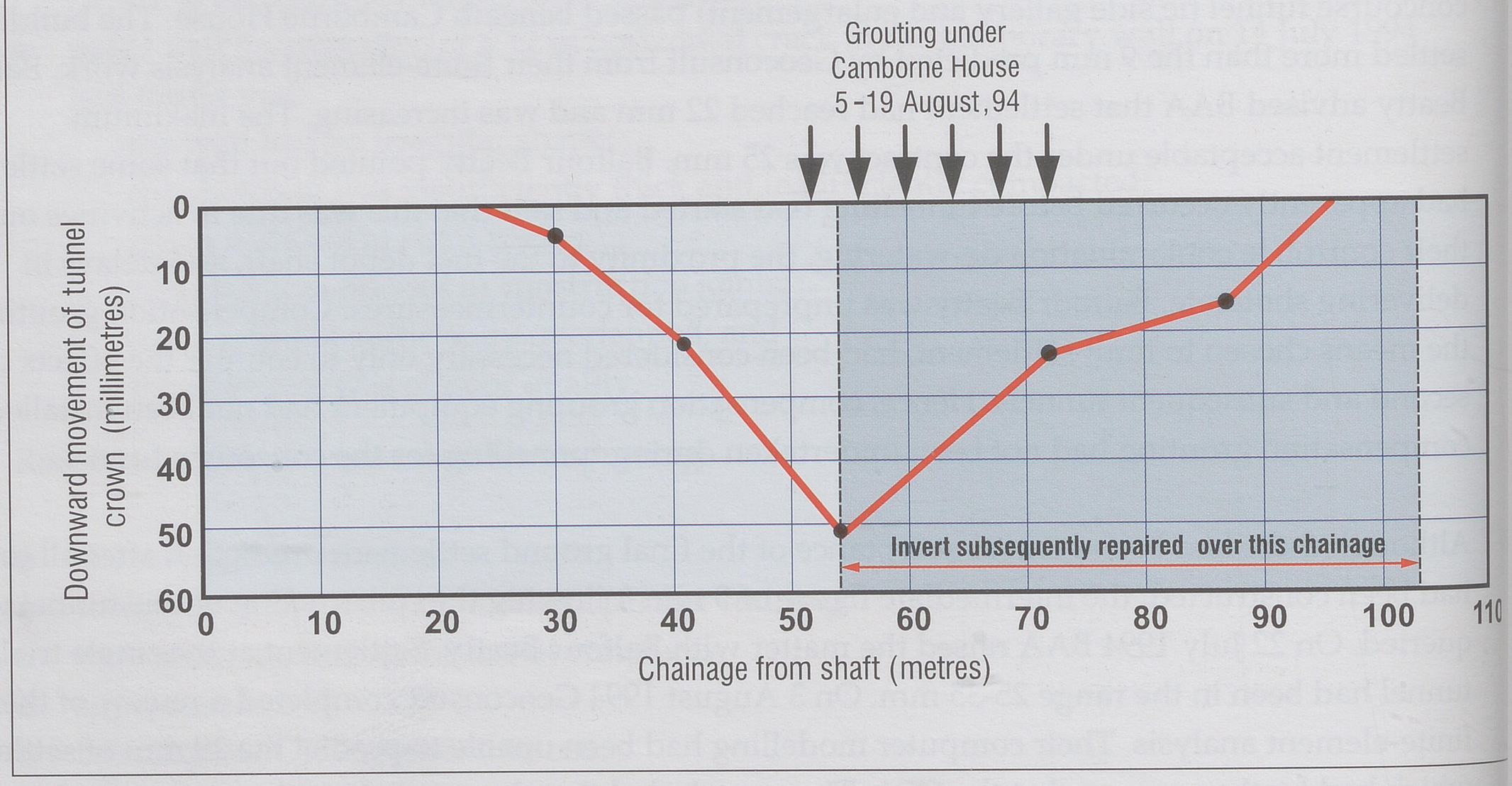


Figure 10 *Additional downward movement of crown of concourse tunnel recorded seven days after grouting under Camborne House*

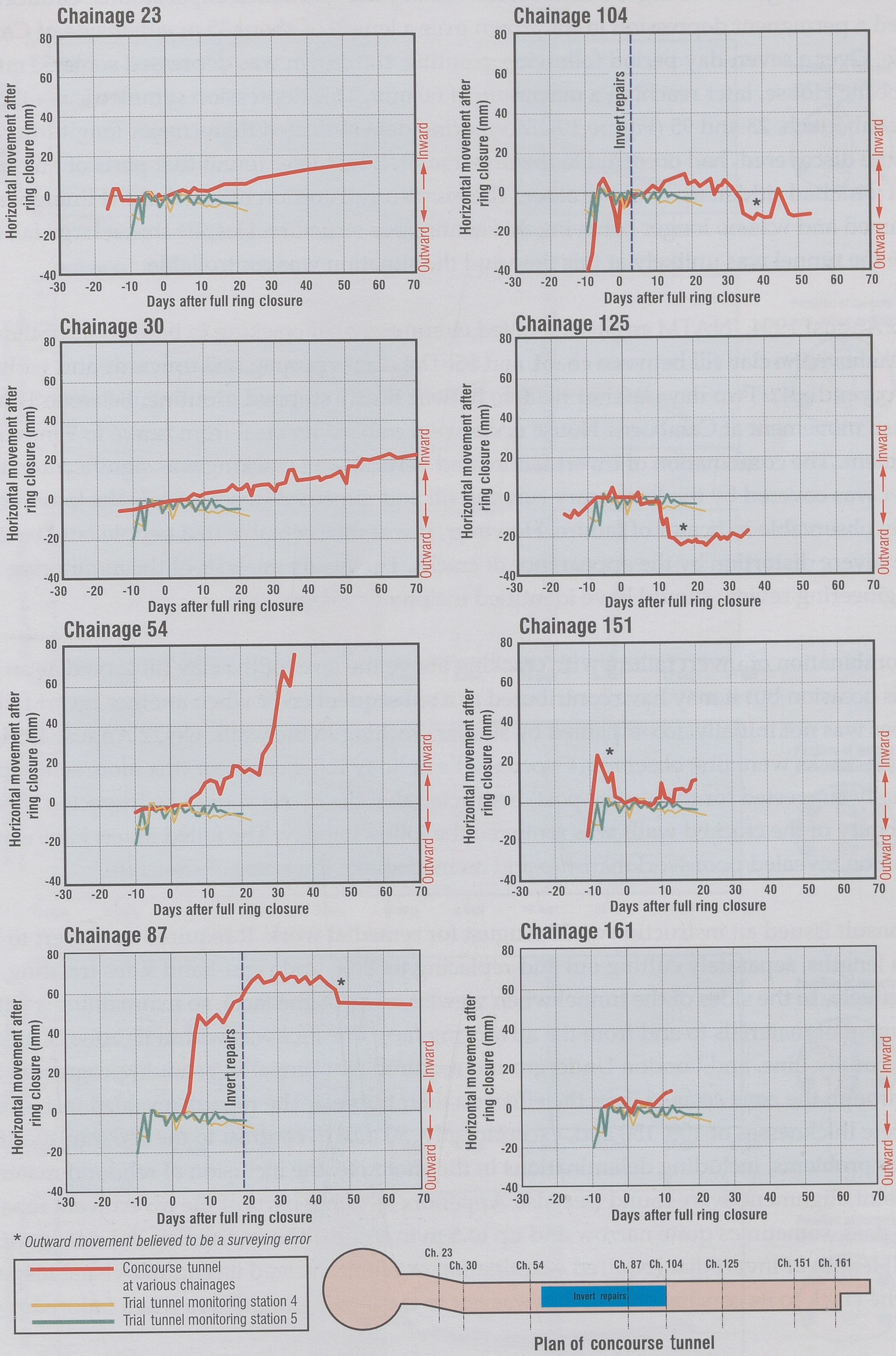


Figure 11 *Movement of the left knees in trial and concourse tunnels*

124 The tunnel lining had undergone distortions well beyond calculated expectations. Grouting had created a permanent depression in the crown over a length of about 35 m either side of Camborne House. Over a seven-day period following grouting, the crown was depressed some 50 mm beneath Camborne House, later reaching a maximum of 60 mm. This depression symmetrically tapered to zero at about ch. 23 and 95 (Figure 10). Monitoring data indicated that a major longitudinal failure, yet to be discovered, had occurred in the invert joint. It was later found that parts of one side of the invert joint had ridden up over the other. The excessive distortion meant that the lining was seriously weakened and was no longer behaving as a continuous structure. Despite this, a large fall of material inside the tunnel was unlikely at this time and the situation was controllable.

125 On 16 August 1994, 'NATM engineers' noted circumferential cracking in both walls of the concourse tunnel above the clay fill between ch. 61 and 65. The cracks propagated upwards and widened (see also Appendix 4). Two days later at 16.00 h, Balfour Beatty stopped grouting. Between 17 and 21 August, movement at Camborne House underwent a sharp reversal from heave to 9 mm of settlement. The combination of invert failure and vertical wall cracking was significant in that the former was covered by the temporary running fill and remained unseen while the latter provided a readily observable indicator of failure. However, it was unacceptable that people only became aware of the severe distortion by the appearance of cracks. The timely analysis of the monitoring data and an engineering review should have identified incipient damage.

126 The combination of invert failure with cracking above the level of the clay fill served as an indicator on this occasion but it may have contributed to a subsequent error when another invert failure during October was not initially accompanied by similar cracking in the walls. On 22 August 1994, six days after the cracks were first observed, Geoconsult's holiday relief engineer (the more senior person originally suggested for the on-site post) instructed that the invert should be inspected. The clay fill in the vicinity of the cracked walls was removed the following day. The failed invert joint was found. Inspection revealed poor workmanship and an inadequate thickness of shotcrete.

127 Geoconsult issued an instruction on 23 August for remedial work. It required the invert to be repaired in 2 m lengths, separately cutting out and replacing the left- and right-hand sides (relating, respectively, to the sides of the tunnel when viewed towards the face), so maintaining a path for the movement of materials to and from the advancing face. The face was within its zone of influence on the Piccadilly Line, and London Underground required that tunnelling should progress at a constant rate through the zone so as to limit the effect on their tunnels. The repairs revealed instances of shotcrete thicknesses of 100, 150 and, exceptionally, 50 mm in contrast to the 300 mm specified. Further problems, including delaminations in the shotcrete, the inclusion of rebound material, and poor joint alignment, were found (see also Appendix 4). Some parts of the invert were repaired in a single pass, sometimes quite narrow and up to 5 m in length. The instruction did not specify the overall length of invert that required examination or repair. Instead it required visual inspection to trace the crack to its conclusion and this was left to the repair gang. There was a failure to:

- consider the available monitoring information;
- carry out a full engineering analysis into the underlying causes of the cracks;
- reassess the risks having regard to the failure; and
- issue satisfactory instructions for the management of the repairs.

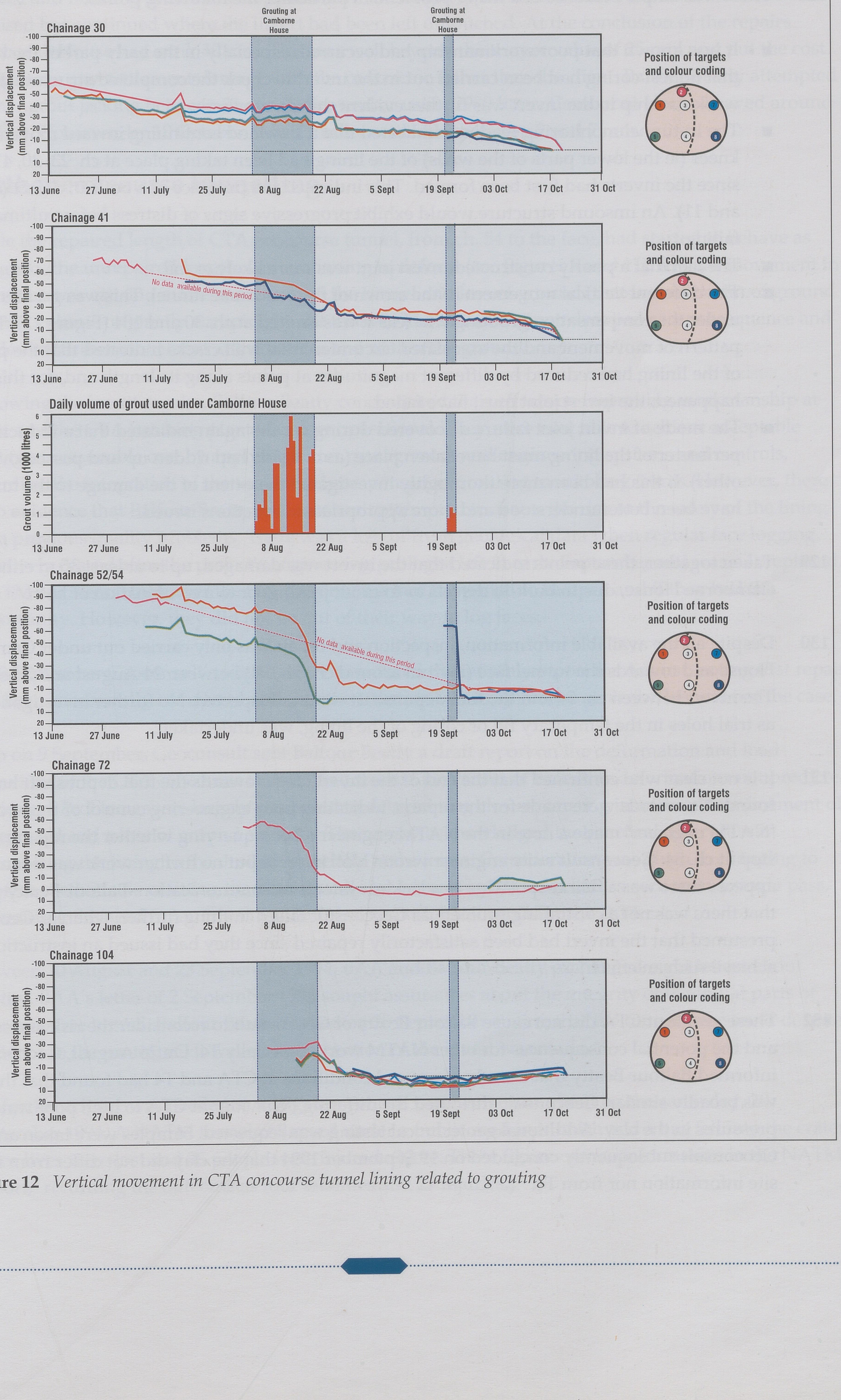


Figure 12 *Vertical movement in CTA concourse tunnel lining related to grouting*

128 There was ample evidence of a major problem, in particular the following points.

- It was known that poor workmanship had occurred, especially in the early part of the tunnel, an that no test coring had been carried out in the invert to check the completed structure. Poor workmanship in the invert was further evident during repairs.
- The in-tunnel monitoring readings indicated that a slow and continuing inward movement of th knees (ie the lower parts of the walls) of the lining had been taking place at ch. 23, 30, 41 and 54 since the inverts had first been formed. This indicated the presence of a built-in defect (Figures 9 and 11). An unsound structure would exhibit progressive signs of distress before ultimately failing.
- The fact that a poorly constructed invert joint was more likely to fail.
- The different vertical movement in the crown of the concourse tunnel. This was greatest directly under the compensation grouting whereas it was limited at ch. 30 and 104 (Figure 12). This pattern of movement and the associated circumferential wall cracks indicated that the perimeter of the lining had reduced by different magnitudes at points along its length and, for this to have happened, the invert joint must have failed.
- The mode of invert joint failure discovered during repairs again indicated that a reduction of the perimeter of the lining must have taken place (as one side had ridden up and passed over the other). If this had been more thoroughly investigated the extent of the damage to the tunnel migh have been better understood and more appropriate instructions issued.

129 Taken together, these points indicated that the invert was damaged, up to at least 35 m either side of Camborne House, due to built-in defects or to grout jacking, or to a combination of both.

130 Despite all the available information, inspection and repair was only carried out under Camborne House and towards the tunnel face (ie from around ch. 54-104) between 24 August and 2 September The invert between ch. 54 and the fuel depot shaft went uninspected. No further investigation, such as trial holes in the temporary fill or coring of the lining, was undertaken.

131 It is not clear who confirmed that the end of the invert crack towards the fuel depot shaft had been found. No records were made for the repairs, indicating poor engineering control of this work. One 'NATM engineer' made a note in the NATM engineer's book querying whether the repairs were to stop at ch. 54. Geoconsult's site engineer wrote 'No!' in reply but no further work was done. It appears there was a 'blind-spot' due to a lack of systems or communication. Balfour Beatty presume that there was not a continuing problem as Geoconsult raised nothing further, whereas Geoconsult presumed that the invert had been satisfactorily repaired since they had issued an instruction to achieve such an effect.

132 These events at CTA did not cause Balfour Beatty or Geoconsult to reconsider the risk assessments and the potential consequences for other NATM work, especially T4. On 26 August, Geoconsult informed Balfour Beatty that a study of ground conditions at CTA and T4 had found that the groun was broadly similar. Geoconsult attributed the differing behaviour at CTA to high pore water pressures in the clay. Additional geotechnical testing was requested. Samples were taken and Geoconsult subsequently concluded on 19 September 1994 that the clay did not differ from the initia site information nor from T4.

133 Surface and building settlement stopped above the length of the tunnel where the invert had been repaired but continued where the invert had been left untouched. At the conclusion of the repairs Camborne House had sunk 40 mm. This was well beyond the trigger value of 25 mm and put the cost of repairing any settlement damage with the contractor rather than the client. Balfour Beatty attempted further grout jacking between 21 and 23 September using 2980 litres. Camborne House heaved around 3-5 mm. However, by 10 October, it had further settled by between 2 and 7 mm.

Further concourse tunnelling

134 While the repaired length of CTA concourse tunnel, from ch. 54 to the face, had started to behave as designed, the unrepaired length was continuing to deform (see Figures 9 and 11). Inward movement in the invert was causing movements around the tunnel and loss of ground (that is, movement of ground into the volume originally occupied by the tunnel). The tunnel's crown dropped as a consequence and this led to further movement at the surface and within the ground.

135 Following the invert repairs, Balfour Beatty concentrated their efforts on improving workmanship at CTA, and the CTA batching plant was now operational. They were now able to achieve acceptable quality at reasonable cost by applying better management and engineering systems and controls, including the integration of the tunnel and compensation grouting monitoring teams. However, there is no evidence that Balfour Beatty or Geoconsult attempted to assess the risk to the safety of the lining from previous quality problems. There was a loss of fresh geological data when regular face logging effectively ceased after the project's engineering geologist left in early September and was not replaced. 'NATM engineers' took over the task but only if a face happened to be open and if they had the opportunity. However, they did not go out of their way to log faces.

136 On 9 September Geoconsult's site engineer completed the monthly report for August, noting that repairs had been successfully completed and that the situation was again under control. This was not the case.

137 Also on 9 September, Geoconsult sent Balfour Beatty a draft report on the deformation and load behaviour of the CTA concourse tunnel. It addressed the causes of excessive deformations not predicted by design. Problems were largely attributed to delayed ring closure causing insufficient confinement of the ground and a loss of ground strength. The review acknowledged the practical difficulties in constructing the lining to the design, especially at the joints. Consideration was given to changing to full-face methods (ie omitting the central wall and advancing the tunnel cross-section in a single pass, so avoiding the need for an invert joint). This approach had been adopted at T4.

138 Between 10 August and 23 September 1994, BAA and Balfour Beatty exchanged eight letters about quality. BAA's letter of 2 September 1994 sought assurances about the integrity of the initial parts of the concourse tunnel. Balfour Beatty replied on 20 September stating that the tunnel was sound despite evidence to the contrary. However, no inspection of the invert was made.

139 If a further trigger was needed to instigate a general review, it came about on the same day, 20 September 1994. A NATM tunnel collapsed under a public road in Munich and a bus fell into the crater. Three lives were lost and 36 people were injured. (Note: These figures revise information in the NATM Report,[1] recording the outcome as four fatalities and 27 injuries.)

140 A further note had been prepared by Geoconsult on 16 September, again suggesting alternatives for the management, processing and presentation of monitoring data and the need for upgraded software. No effective changes were made.

141 Balfour Beatty was again challenged by BAA on the integrity of the concourse tunnel at a meeting on 26 September when BAA's CTA construction superintendent tabled a longitudinal plot of the tunnel. The computer software used by Geoconsult did not produce such plots. The plot, broadly similar to Figure 10, showed the depression adversely affecting the crown of the unrepaired concourse tunnel between the fuel depot shaft and Camborne House. A copy of Balfour Beatty's letter of 20 September had yet to reach the BAA CTA team and, likewise, information that BAA's senior managers had accepted Balfour Beatty's reassurances. When the construction superintendent became aware of these developments, he reluctantly formed the view that he could do no more.

142 At CTA, the in-tunnel monitoring data (Figures 7, 8, 9 and 11) indicated ongoing movement in the unrepaired section of the tunnel. By mid-September, the strain was continuing to increase and showed no signs of stopping. Between the fuel depot shaft and ch. 54, movement was continuing at a fairly uniform rate.

The start of further tunnelling 'north'

143 Balfour Beatty's initial plan had been sequentially to construct the CTA concourse tunnel, the up-line platform tunnel and then the down-line platform tunnel with the permanent lining work then following on. However, progress had not been at the rate of 3 m/day initially estimated nor the rate of 4.8 m/day used in the work programme. Instead, it was only around 1.3-1.7 m/day, the same as achieved at the trial tunnel. The consequence was that the CTA was falling behind programme and key completion dates would be missed. BAA was applying pressure for completion to the original programme and there had been considerable correspondence. Geoconsult had concluded that output could be improved. Balfour Beatty carried out a review and also concluded that performance could be improved, but not to the level initially predicted. Balfour Beatty's tender submission had included the use of specialised excavation plant but this was not subsequently used.

144 Driving the platform tunnels would inevitably add to the load on the concourse tunnel. The plan, based on Geoconsult's design, had been to stagger the platform tunnel drives by at least 20 m (ie a longitudinal separation of two tunnel diameters) to minimise the effect on the concourse tunnel. Under pressure to make up time, Balfour Beatty chose to drive both platform tunnels together, so maximising the adverse effect. This decision was taken despite the unresolved issues of quality and structural integrity reflected by indications of ongoing movements in the concourse tunnel. Geoconsult raised no objection and neither did any other party. The down-line platform tunnel 'north' was started on 21 September 1994. Balfour Beatty's project director paid an extended visit to the CTA tunnel system with his tunnel superintendent two days later. From visual examination, their subjective assessment was that the clay face of the new drive was particularly soft, suggesting to them that the ground was weaker and that conditions were different from those found when the concourse tunnel was excavated. The next day the project director instructed the engineering manager that others should be shown the soft clay as a demonstration of the perceived difference between the ground at CTA and T4. There was no request to recheck the design or take samples; and no other

action was taken to follow up and explain the observations. As a result of this absence of further investigation, it is a matter of conjecture as to what might have caused the ground in this area to be soft, but earlier shaft construction and tunnelling is a probable reason. The third tunnel, the up-line platform tunnel 'north', was started this same day.

145 By 2 October, 117 corrective action requests had been raised in respect of the CTA tunnels.

Events in the closing days

146 Following the start of the two CTA platform tunnel drives 'north', the ongoing movements in the concourse tunnel began to accelerate from around 7 October (see Figures 7, 8 and 12), indicating that the tunnel was unsound. Convergence in the walls could not have occurred to the degree that it had without a failure of the invert. If ignored, there would eventually be a collapse (see Appendix 4). Movements were confined to the unrepaired length of the tunnel. While some further movement was to be anticipated due to driving the other tunnels, the nature, scale and direction of the adverse movement was sufficiently alarming that it should have alerted people to a major problem. Only radical measures could have succeeded in preventing the impending disaster.

147 Had a surface contour map been prepared, it would have shown that a shallow depression was developing over the CTA concourse tunnel with the centre of the depression at ch. 30 (Figure 13). Such drawings can be easily provided. However, the project was only preparing cross-sections, making interpretation more difficult. Problems at ch. 30 were also identifiable by an extensometer on MMS II. It indicated that there was increasing vertical movement in the clay at invert level (see Figure 14).

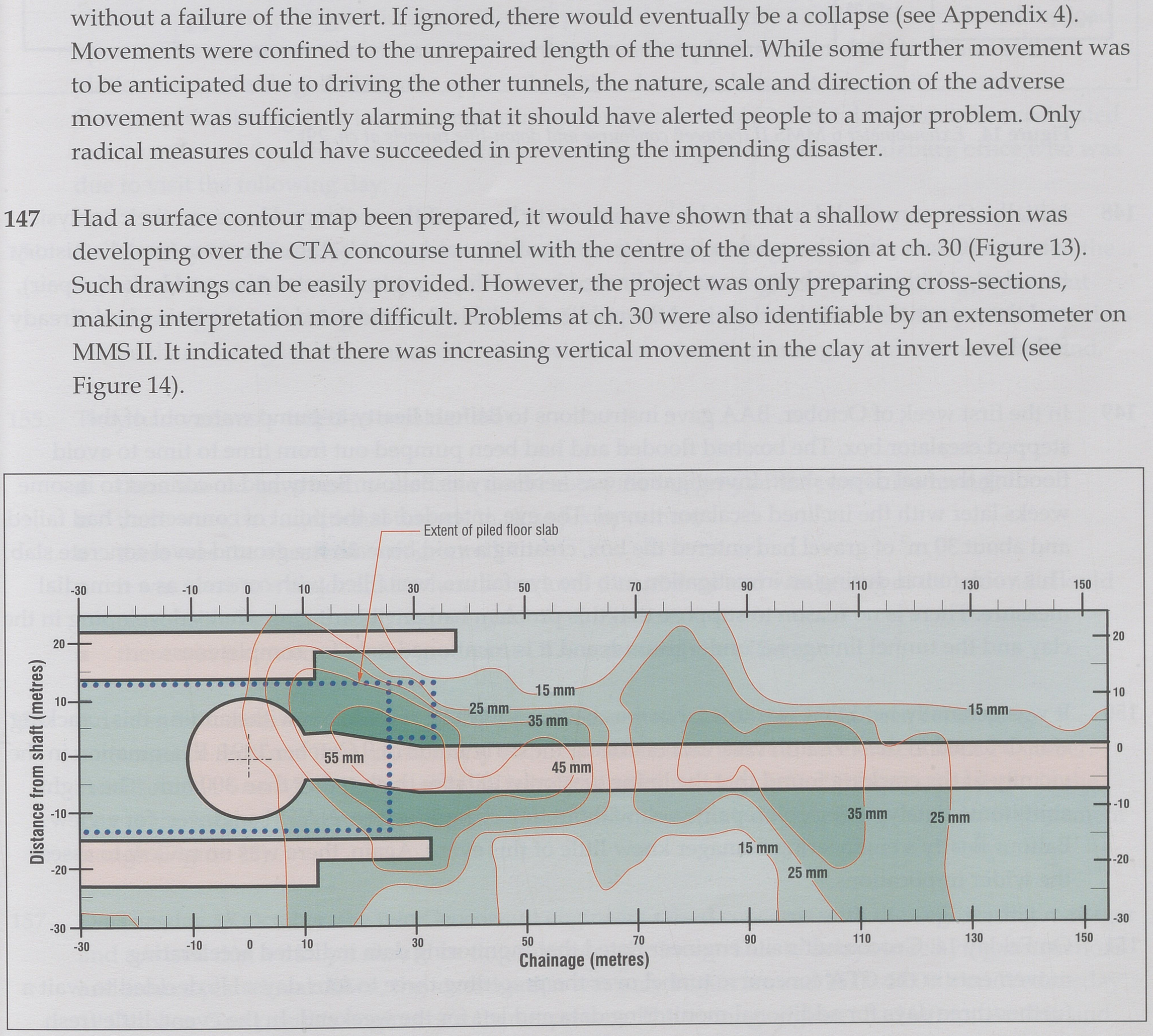


Figure 13 *Contours showing surface settlement above the tunnel complex before the collapse*

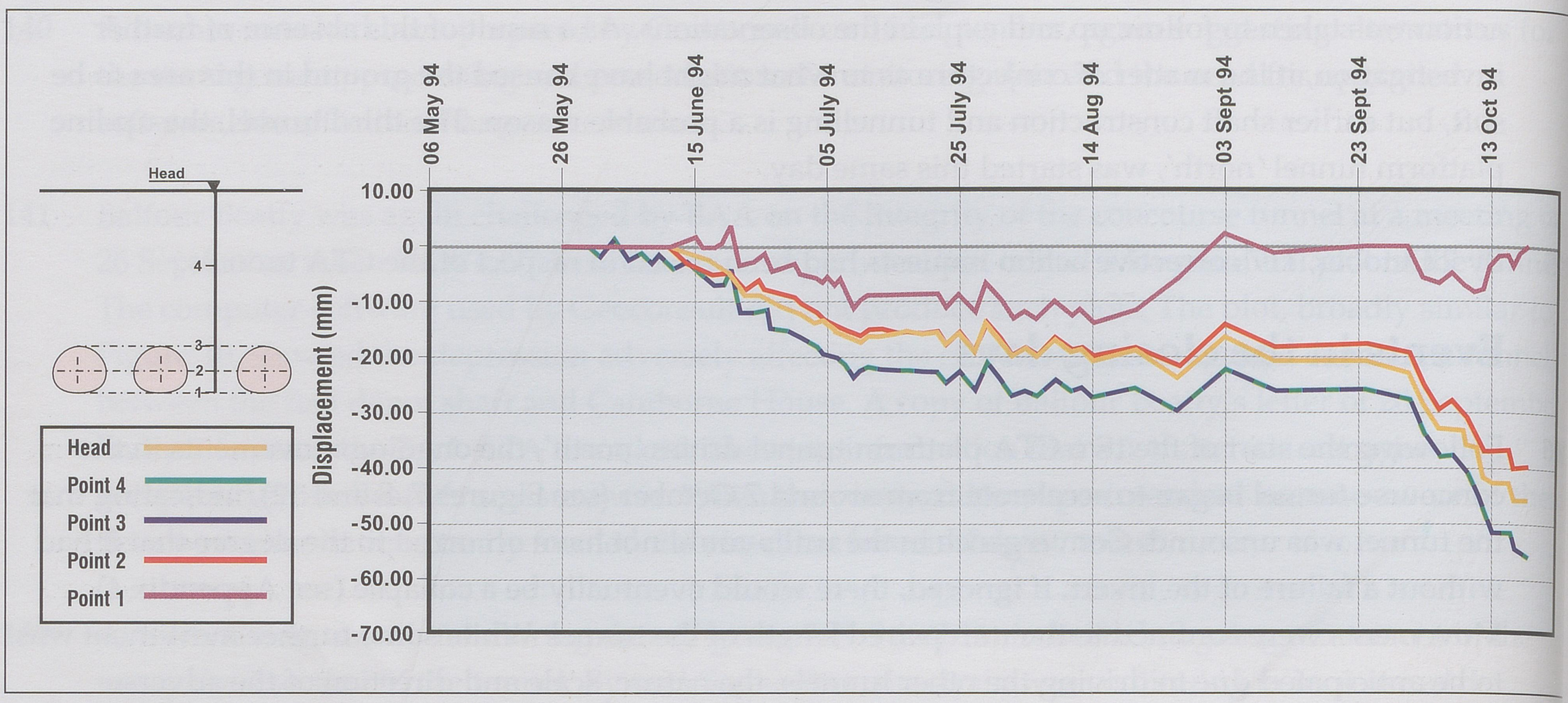


Figure 14 *Extensometer 6 MMS II (between concourse and down-line tunnels at ch. 29)*

148 Initially, Geoconsult did not consider movements to be out of the ordinary. However, their analysis was insufficient given the construction of three closely spaced tunnels, the concourse tunnel's history (ie a design lacking in robustness and of limited buidability, its poor construction and lack of repair), and the potential risks to workers and the public. Available data indicated that the lining had already failed.

149 In the first week of October, BAA gave instructions to Balfour Beatty to pump water out of the stepped escalator box. The box had flooded and had been pumped out from time to time to avoid flooding the fuel depot shaft. Investigation was necessary as Balfour Beatty had to connect to it some weeks later with the inclined escalator tunnel. The eye, intended as the point of connection, had failed and about 30 m^3 of gravel had entered the box, creating a void beneath the ground-level concrete slab. This void, found during an investigation into the eye failure, was filled with concrete as a remedial measure. There is no reason to suppose that this problem had any bearing on events developing in the clay and the tunnel linings far underground; and it is mentioned only for completeness.

150 It was generally held that workmanship was better at T4 than at CTA. Notwithstanding this, cracking was detected in the T4 south vent tunnel during the early hours of 9 October 1994. Examination in the vicinity of the cracking found that the lining was only 100 mm thick rather than 300 mm. The night shift immediately undertook repair work without first consulting the 'NATM engineer' for a view. Balfour Beatty's engineering manager knew little of this event. Again, there was no review to assess the wider implications.

151 On Friday 14, Geoconsult's site engineer noted that monitoring data indicated accelerating movements in the CTA concourse tunnel over the preceding three to four days. He decided to wait a further three days for additional monitoring data and left for the weekend. In the event, little fresh data were collected.

152 One crucial objective of monitoring should be to ensure that there is sufficient time for the successful

completion of pre-planned contingency actions (see the discovery-recovery model in the NATM Report[1]). However, time had been lost in identifying the trend, additional convergence had taken place and the rate of change was accelerating. This failure to discover and identify the inadequate performance of the concourse tunnel lining was serious. Improved computer software might have made the task easier. However, based on the available data and the history of the concourse tunnel, more positive steps should have been taken.

Accelerating failure

153 On Monday 17 October, Geoconsult's site engineer saw that accelerated movements in the concourse tunnel were continuing, particularly at around ch. 30 and 41. Ch. 30 is broadly at the periphery of the large subsurface concrete box founded on augured piles. It may be that the piles had some positive effect in supporting the ground above the first part of the concourse tunnel and so reduced the load upon it. The concourse tunnel was closest to the down-line platform tunnel at ch. 30 and both platform tunnel side galleries were approaching this chainage; hence, it was a critical area. Geoconsult's site engineer told the engineering manager, possibly on that day, about the accelerated movements and decided to discuss matters with a senior engineer from the Salzburg office who was due to visit the following day.

154 On Monday 17 or Tuesday 18 October, Balfour Beatty's engineering manager visually inspected the concourse tunnel but saw nothing untoward. Geoconsult's site engineer had similarly looked but found no signs of cracking above the fill level. Erroneously, they concluded that the position was less severe than in August and continued in this belief even when the damaged invert was later found.

155 They had variously failed to consider that:

- there should have been reasonable doubt about the integrity of the concourse tunnel;
- there were two additional tunnels in close juxtaposition;
- there was the observed 'soft ground';
- it was close to a major shaft where some local disturbance and weakening of the ground should reasonably be anticipated; and
- there was a concern that the ground at CTA was somehow different.

156 Adverse indicators were present. The available data showed that there had been continuing convergence for some time, particularly at ch. 30 and 41, and this had accelerated from 7 October. Extensometer 6 on MMS II (Figure 14) was indicating increasing vertical compressive strain in the clay at the level of the concourse tunnel's invert and there was a developing ground-level settlement trough (Figure 13).

157 On Tuesday 18 October, the two Geoconsult engineers raised concerns with the engineering manager and advised that a trial pit should be dug to expose the invert. Due to delays in relaying instructions and from a plant breakdown, the investigation was only begun around 16.00-17.00 h on Wednesday 19 October. Geoconsult's engineers were not present. The visiting engineer had left for Austria and Geoconsult's site engineer was in his office. This was a serious omission as it was essential to determine the cause of the movement and Geoconsult were in a unique position to provide expert

advice and instructions for repairs. Likewise, Balfour Beatty's engineering team failed to become sufficiently involved.

158 Investigation revealed a defective invert. By chance, a 'NATM engineer' was in the concourse tunnel at the time. He had not been told about the investigation and its purpose. He carried out some simple hammer tests and then went to the site offices. He met Geoconsult's site engineer who said that he would prepare an instruction the following morning for repairs to be carried out in like manner to those in August. However, no written instruction was ever issued.

159 Concourse tunnel repairs, following the general pattern of those in August, were started by the night shift on the verbal instructions of the tunnel superintendent and site agent and without further engineering analysis. Some five separate repairs were made by the two gangs (the concourse gang and the up-line gang) who were put on the work. A crack in the left-hand side wall (when viewed from the fuel depot shaft) at about ch. 18 was repaired by replacing the invert. Repair of a further crack near the shaft eye was started but not completed that shift. A 2 m length of invert was replaced further into the concourse tunnel around ch. 20-30 where it had been inspected by the day shift; and also two adjacent patches each 2 m long. Without clear engineering direction, the work was unplanned and ad hoc.

160 Meanwhile, a third gang opened up fresh work in the down-line platform tunnel 'north' by excavating a crown section in the side gallery and also a bench and crown in the enlargement. Contrary to good practice and lacking proper engineering instructions, they did not focus on closing down work for the duration of the repairs.

161 On Thursday 20 October there was a routine meeting between Balfour Beatty and BAA to consider engineering matters including progress with design work. The issue of repairs to the concourse tunnel invert was not raised as a topic for discussion.

Day shift, Thursday 20 October 1994

162 Some site staff were absent from the day shift. Balfour Beatty's 'NATM engineer' was only at work between 07.00 and 10.00 h due to illness. The project director was unwell and was absent from site. BAA's CTA construction superintendent had just returned from sick leave. He did not visit the tunnels due to an extended morning meeting and further illness that afternoon. BAA's CTA area manager was on leave. Balfour Beatty's CTA site agent spent the day in his office. He was preparing to meet the following day with a new Balfour Beatty director who had taken over responsibility for the project. Among other matters, lack of progress was due to be discussed. They thought, with good reason, that the director would be discontented to learn of more delay and repairs. Little supervision and senior management control was therefore applied by Balfour Beatty to the crucial task of invert repairs; and BAA's team was similarly depleted.

163 At about 08.30 h the CTA site agent was told by the section agent that shotcrete in the concourse tunnel invert immediately adjacent to the tunnel eye had been found to be in good condition but too high and that work had started to break it out in order to reform it at the correct level. The removal of satisfactory invert in such a crucial location did not represent good engineering judgement. As work

had started, the agent was content for it to continue. Neither the engineering manager nor Geoconsult's site engineer had been involved in the decision. Instead, the initial decision had been taken at a junior level in the production team. This was further indicative of the lack of engineering control. At about 09.30 h the tunnel superintendent visited site and made enquiries about the work. He then met with the agent and they belatedly agreed that it was inappropriate to remove undamaged invert.

164 Geoconsult's site engineer visited the CTA site at 09.30 h and visually inspected two open repairs. He saw some cracked inverts and considered them to be similar to but not as bad as those in August. He was satisfied with Balfour Beatty's actions and gave verbal instructions for repairs to be carried out in the manner of those in August.

165 Fresh tunnelling work in the concourse and up-line tunnels remained suspended so that repairs could be completed. Repairs continued throughout the day. People variously noted vertical cracks developing a few metres from the eye in both walls of the concourse tunnel; but, crucially, no one thought it necessary to question why cracks in such a critical section of the tunnel system were appearing. Two repairs were completed, one between ch. 13 and 15 and one between ch. 18 and 20 which also took in a further adjacent area of defective shotcrete. Temporary fill had been removed from the invert, from the eye up to ch. 21, to permit these repairs to be made.

166 A BAA shift engineer visited site and found that the exposed invert shotcrete was thin. By chance, Balfour Beatty's quality assurance manager conducted an audit on shotcrete batching at CTA. He found that some shotcrete was left standing for an hour before use and that clay was entering the aggregate bins, contaminating its contents. More positively, he noted that a change of an additive, used to accelerate the gain in strength of the shotcrete, provided improved long-term strength. BAA's site safety manager also visited but did not appreciate the significance of the work in hand.

167 Fill was further removed around ch. 25-35 and circumferential cracking was seen to develop. Again, this clear and most worrying indicator of lining instability was not acted upon. Work continued in the down-line platform tunnel 'north'. A 2 m length of invert was excavated and a thin sealing coat of shotcrete was applied during the afternoon. It was left for the night shift to complete.

168 No risk assessment was carried out for the repairs. Indeed, there was no understanding of the safety implications connected with the repair work. Repairs were ad hoc and they failed to comply with the August instruction for staggered 2 m lengths. The work was not under the control of the engineering team. Instead, it was led by the local construction team who lacked knowledge about the design, the monitored performance of the linings and the potential consequences of their actions on the strength of the ground. Geoconsult's site engineer next inspected the ongoing repairs at 16.00 h and was content. Progress had apparently been slow. He then left site.

169 Around 17.00-18.30 h, shotcrete began to spall (ie the break-away of surface material) from the lining in the vicinity of the eye. Signs of fresh movement were detected at two completed repairs near the eye. Vertical cracking close to the eye had worsened.

The incident

Night shift, Thursday 20 October 1994

19.00 h

170 On 20 October 1994 the CTA night shift commenced as usual at 19.00 h with three gangs each under the supervision of a leading miner.

171 There was little NATM experience among Balfour Beatty's engineering, supervisory and works teams that night. The engineering team was represented by one of the four junior 'NATM engineers'. Representing the supervisory team was a section agent, the most senior man on the shift with 15 years civil engineering experience but none with NATM; a section engineer who likewise had no previous NATM experience; a junior engineer who had some limited knowledge of NATM estimating; and the pit boss who had been a coal miner for 20 years and in civil engineering for four. He had been promoted from miner to leading miner five or six weeks previously and had been further promoted to pit boss commencing with this shift. There were no other senior staff on site.

172 Gangs went to the concourse tunnel and the down-line platform tunnel 'north'. The up-line platform tunnel 'north' drive had been sealed with shotcrete and the face buttressed with spoil to enhance stability. Repair work continued at the discretion of Balfour Beatty's local CTA staff. Miners initially set to work where they had broadly worked the previous shift.

173 The site agent directed that a developing crack close to the right-hand side of the eye should be given priority and that work should at last be put in hand to close up the down-line platform tunnel 'north' during repair work. An ad hoc approach continued throughout the shift and concentrated on repairing developing wall cracks close to the eye and around ch. 25-30.

174 The side gallery of the down-line platform tunnel 'north' face had reached a point contiguous with ch. 30 of the concourse tunnel and was in a zone of sheared clay surrounding the concourse tunnel lining. The concourse tunnel had not been temporarily stabilised to prevent further movement in the lining and further ground movements took place as a consequence, causing increased disturbance to the clay, further weakening it. The tunnels were progressively subjected to a pattern of loading they were not designed to support.

175 The tunnel superintendent and the site agent left site at the end of their shift around 20.00 h. Just before leaving, the tunnel superintendent appears to have been the first to express some concern about developing events but nothing positive was done.

176 A single BAA shift engineer was on duty at CTA to cover the tunnelling and widespread surface works. Sometime between 20.00 and 21.00 h he noted that the concourse tunnel invert had suffered extensive failure. There was a mixture of broken shotcrete and clay. The invert appeared to have

heaved and broken into pieces rather than simply cracked. In some places, one-half of the invert had visibly ridden up over the other. The lining had suffered a major heave failure in the invert and was clearly badly damaged. Miners showed him the vertical cracks near the eye. However, the BAA engineer had no tunnelling experience and, like others, did not appreciate the significance of what he had seen. He was then drawn away to another worksite.

177 Spalling continued near the eye and was probably due to movement at the construction joint between the heavily reinforced eye and the NATM lining. It was a further clear indicator of the developing collapse. Once more, the tell-tale signals and their significance were missed.

Around 20.30-21.00 h

178 A piece of shotcrete fell from the face of the down-line platform tunnel 'north', indicating the first visible sign of serious distress in the tunnel heading and the clay surrounding it. Shortly after this, hairline cracking was observed in the face.

Around 22.30 h

179 By now, serious longitudinal cracking had appeared in both walls of the down-line platform tunnel 'north' side gallery. These were examined by the site team and repairs were proposed. However, the cracking indicated that collapse was imminent and that people were exposed to serious risk.

180 The ground around the heading had become weakened by the deformation it had undergone and by the loads it had to bear. Deformation had been caused by the long-term and continuing movements in the concourse tunnel walls. As the concourse tunnel wall closest to the down-line platform tunnel moved inwards, the ground between the two tunnels lost its restraining support, causing further deformation and loss of strength.

181 The BAA shift engineer briefly returned and photographed the cracks propagating in the concourse tunnel and the invert failure but again failed to appreciate their significance. Miners were instructed by the pit boss to repair cracks and do no more excavation.

182 It should have been plainly evident to an experienced NATM supervisor that collapse was inevitable and that instructions for the evacuation of the whole of the CTA works were necessary and urgent. Cracking continued to develop. In the down-line platform tunnel 'north', cracks propagated back to the enlarged section. Simultaneously, the clay between the concourse tunnel and the down-line platform tunnel 'north' drive progressively yielded.

Around 23.15 h

183 The 'NATM engineer' visited site for the first time that shift. He found that the temporary fill had been removed to about ch. 40 of the concourse tunnel and that there was severe damage at about ch. 30. The left-hand wall was cracked vertically. The crack was some 50 mm wide at the invert, reducing towards its upper end high in the bench. The crack showed differential inward movement of the order of 30-50 mm at the knee, with the section closest to the face more advanced. The left

side of the invert appeared to have ridden up over the right. Similar invert failure was present elsewhere in the concourse tunnel (see Appendix 4 and Figure 29). Repairs in hand at ch. 30 involved breaking out shotcrete in parts of the lower section of the bench and the invert. Close to the eye a repair had been completed to one wall and mesh was being bolted to the opposing wall as the first step in a further repair.

184 In the up-line tunnel 'north', short runs of horizontal shear cracking, commonly terminating in vertical cracking, had developed in the temporary wall of the side gallery over the full length of the bench. In the down-line tunnel, except for the initial 5 m, there was similar but more severe cracking in the left-hand wall of the side gallery. The horizontal cracks had opened to about 30 mm and shotcrete was spalling from the surface. In the wider cracks, distorted mesh could be seen. This suggested that the crown section was dropping around the outside of the remainder.

185 Balfour Beatty's shift engineer photographed the down-line platform tunnel 'north'. The section agent became concerned. He instructed that the faces of both platform tunnels should be re-meshed and shotcreted. This started around 23.40 h in the down-line but nothing was done in the up-line due to limited resources. Cracks in the concourse tunnel were growing and there was increasing spalling at the eye.

Around 23.30 h

186 Cracking had worsened in the left-hand wall of the down-line and was developing in the side gallery head wall. A miner unable to assist others in making high-level wall repairs in the concourse tunnel started to remove invert shotcrete at about ch.18 where there was some surface damage but the invert was otherwise satisfactory. Other miners were beginning to become concerned and some decided to leave the tunnels for the relative safety of the shaft bottom. The lining could have collapsed at any time and people in the tunnels were at very serious risk.

Around 23.45 h

187 The 'NATM engineer' noted that the crown of the down-line platform tunnel 'north' had dropped about 25 mm in an hour.

Around midnight

188 The inexperienced supervisory staff continued to keep the gangs underground. However, the section agent and the 'NATM engineer' had become sufficiently concerned that they recognised the need for assistance. The section agent phoned the site agent. The section agent and the 'NATM engineer' then separately left site respectively to collect the tunnel superintendent and Geoconsult's site engineer. As the latter had no telephone, it meant travelling in the hope that he was at home. Cracking continued. A miner told the pit boss that people should not be working in the tunnels. The pit boss may have independently started to instruct the initial evacuation of the down-line platform tunnel 'north' at about this time.

Friday 21 October 1994

Around 00.15 h

189 The section engineer, a leading miner and the pit boss inspected the concourse tunnel for cracks over its entire length, travelling a considerable distance from relative safety at the bottom of the shaft. They found that recent concourse tunnel invert repairs had badly deformed by heaving and that mesh had deformed and had risen up out of the partially set shotcrete.

Around 00.30 h

190 The pit boss told some miners to leave the concourse tunnel. One continued to shotcrete a repair at ch. 24. Some miners were still working in the down-line platform tunnel 'north' where the last activity, shotcreting, was drawing to a close. The site agent arrived at site followed by the tunnel superintendent who had returned with the section agent. Geoconsult's site engineer and the 'NATM engineer' arrived shortly after.

Around 00.30-00.45 h

191 Cracking had worsened in the central wall of the up-line. In the down-line side gallery the central wall was extensively damaged by horizontal cracking and surface shotcrete was spalling. The crown section appeared to be dropping around the outside of the remainder at shear cracks in both walls. The face had suffered extensive vertical cracking. The crown had fractured longitudinally at the face and the failure was propagating along the tunnel.

192 The site agent, the section agent, and the tunnel superintendent entered the tunnels and examined them. Some miners stood in or near the base of the shaft. The tunnel superintendent told a shotcreter who was continuing to work in the concourse tunnel to leave. Spalling had substantially increased. One miner saw that dust was rising from the invert of the concourse tunnel, indicating that movement was taking place.

Around 00.45 h

193 Cracking continued to develop throughout the tunnels. Fragments of shotcrete began to spall from the crown of the down-line. Further spalling was seen some 5 m into the concourse tunnel.

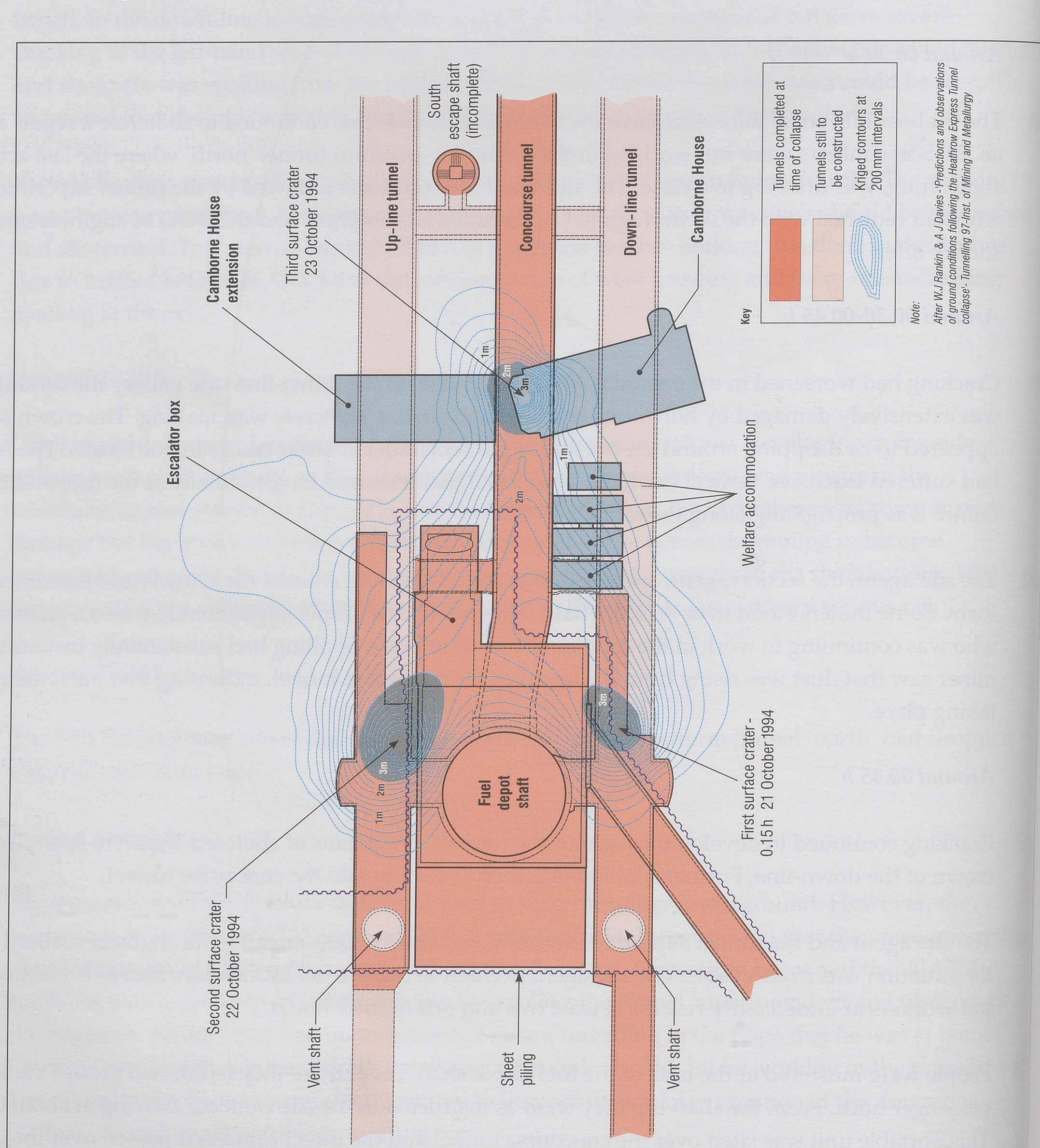
194 The site agent and the tunnel superintendent and, separately, Geoconsult's site engineer realised that the situation was irretrievable. The site agent decided to order a full evacuation. Previous inaction had put workers at unnecessary risk for at least two and one quarter hours.

195 People were mustered at the base of the fuel depot shaft. From there they left in two groups via a passenger hoist. From the shaft top they went as instructed to the site canteen, arriving at about 00.50 h. This portable unit was sited over the concourse tunnel and the direct route to it passed over the down-line platform tunnel 'north'. As site staff from the second group were walking towards Camborne House, they felt the ground move. The pit boss ordered a further evacuation, this time to clear the site,

less than 5 minutes after some miners had arrived at the canteen. The ground was moving as people left the canteen which had begun to tilt.

Around 01.15 h

196 The tunnel system suffered rapid major failure. A collapse propagated from the down-line platform tunnel 'north' to the surface where, shortly before, people had passed on their way to the canteen and offices (Figure 15). The initial length of the concourse tunnel also collapsed.



Note:

After W.J Rankin & A J Davies - 'Predictions and observations of ground conditions following the Heathrow Express Tunnel collapse'- Tunnelling 97-Inst. of Mining and Metallurgy

Figure 15 *Surface effects of tunnel collapses*

Emergency response and damage

197 BAA's shift engineer returned to site soon after the collapse and was informed. He was the first person from BAA to be told about the developing situation, despite the risks to the Piccadilly Line and the nearby roads and car parks (see Figure 2).

198 Rather than inform the airport duty manager, responsible for the safe operation of the airport, as required by BAA's emergency procedures, Balfour Beatty dialled 999 for the off-site emergency services. The local fire service informed the airport fire service who in turn alerted the Heathrow Operations Centre at 01.21 h. The first message was confused, only mentioning a diesel tank leak. The full extent of the event became clear to the airport's operations staff when the duty manager attended the scene a few minutes later. London Underground was then contacted. Fortunately, their scheduled services had stopped for the night.

199 Key people from all involved parties were notified and arrived at site over the next few hours. The first of a series of emergency meetings was convened in an off-site conference room. The immediate concerns included:

- safety of personnel and the public;
- informing relevant post holders;
- controlling access to the site;
- risk of damage to services and airport facilities;
- risk of damage to the Piccadilly Line;
- isolation of the power supply to Camborne House;
- re-establishment of the ground monitoring instrumentation;
- establishment of additional surface monitoring points.

200 There was a failure immediately to establish a sufficiently large exclusion zone. The surviving tunnel linings were potentially unstable and further collapses that might have put people outside the site boundary at risk could not be ruled out. No steps were taken immediately to close surface structures such as car parks 1A and 3, subsurface structures such as the pedestrian subway systems, the Piccadilly Line, roadways and pedestrian routes that were at risk.

201 Information normally remotely gathered by electronic means about the settlement of CTA buildings was initially lost. It was re-established by 05.00 h. Until then visual checks were made. However, these were no substitute for a wide exclusion area in the initial hours. London Underground independently decided at 03.56 h not to reopen the Piccadilly Line.

202 Following the initial emergency meeting, BAA made space available to Balfour Beatty for an off-site incident control room and for the instrument monitoring team. Further liaison meetings were arranged, initially every 2 h, to monitor developments and co-ordinate action.

203 A limited inspection was made around midday on Friday 21 October by entering the fuel depot shaft.

Figure 16 *CTA concourse tunnel eye before the collapse. The eye passes through the heavy fuel depot shaft. The walls of the NATM lining can be seen in the tunnel and also the temporary clay running surface (Reproduced with the permission of Balfour Beatty)*

Figure 17 *CTA concourse tunnel eye after the collapse. The NATM lining has dropped and the crown is now visible from the shaft. The broken invert has rotated through 90° and parts stand on end (Reproduced with the permission of Balfour Beatty)*

It was found that the eye of the down-line was completely filled with collapsed material. The crown of the concourse tunnel had dropped severely and the invert appeared to have failed by hinging upwards about both knees (Figures 16 and 17). The up-line tunnel was severely cracked and further movement could be heard. The inspection team quickly left the fuel depot shaft.

204 Collapses continued over a number of days. The initial collapse had affected the short down-line platform tunnel 'north', its cross-passage to the fuel depot shaft and a more substantial length of the concourse tunnel. The up-line platform tunnel 'north' subsequently failed on the afternoon of Saturday 22 October 1994, causing a further surface crater (Figure 15). Camborne House and its adjacent extension suffered severe damage on Sunday 23 October 1994. The buildings partially collapsed and were subsequently demolished (Figure 18). Chester Road did not in the event exhibit signs of any noticeable settlement. It was subsequently closed to create working space. Major traffic chaos occurred until a new one-way system was brought into effect. Passengers were denied use of subway links to Terminal 3 and had to manoeuvre luggage trolleys at ground level.

Figure 18 *CTA fuel depot site after the collapse, taken from car park 3. The 19 m diameter shaft is in the mid-ground with the canteen and welfare units beyond. Camborne House Extension exhibits extreme distress at its right-hand end. Camborne House has been demolished*

205 The fuel depot shaft was later filled to above the tunnel eyes with concrete, so securing the shaft, but preventing further investigation by direct observation. A 1.7 m diameter cased augured bore hole was formed east of car park 3 and was used to make entry into the down-line platform tunnel 'south' for the purposes of inspection. The tunnel had flooded to a depth of 2 m with water contaminated by diesel fuel but appeared otherwise intact. The up-line platform tunnel 'south' was later found to be flooded to a depth of nearly 4 m when inspected via a remotely operated camera lowered down a smaller bore hole. The surviving CTA tunnels and voids under Chester Road were filled with concrete, placed via augured bore holes, to secure the structural integrity of car parks 1A and 3, the Piccadilly Line and surface infrastructure. Some 8000 m^3 of concrete was eventually used. Work initially concentrated on forming a plug in the concourse tunnel under Chester Road to prevent any further progressive collapse of the tunnel. Access to the concourse tunnel was later achieved by a temporary extension to the 'north' escape shaft and a heading. The tunnel was found to be dry, filled with concrete up to bench level and with the plug at Chester Road reaching the crown. There were no visible signs of damage. Grout was pumped into voids in the ground over the general area of the CTA worksite.

206 Strengthening work involving colliery arches was undertaken at the T4 vent tunnels as a precautionary measure before reopening the Piccadilly Line. On 30 October 1994 severe and uncontrolled cracking occurred in the invert of the north vent tunnel when the temporary fill was removed as a first step in the strengthening works. The problem was remedied by the immediate placement of *in situ* concrete on the invert. Poor workmanship was found when invert panels were later removed as a part of HSE's investigation. Joints were below the specified thickness and improperly formed (Figures 19 and 20).

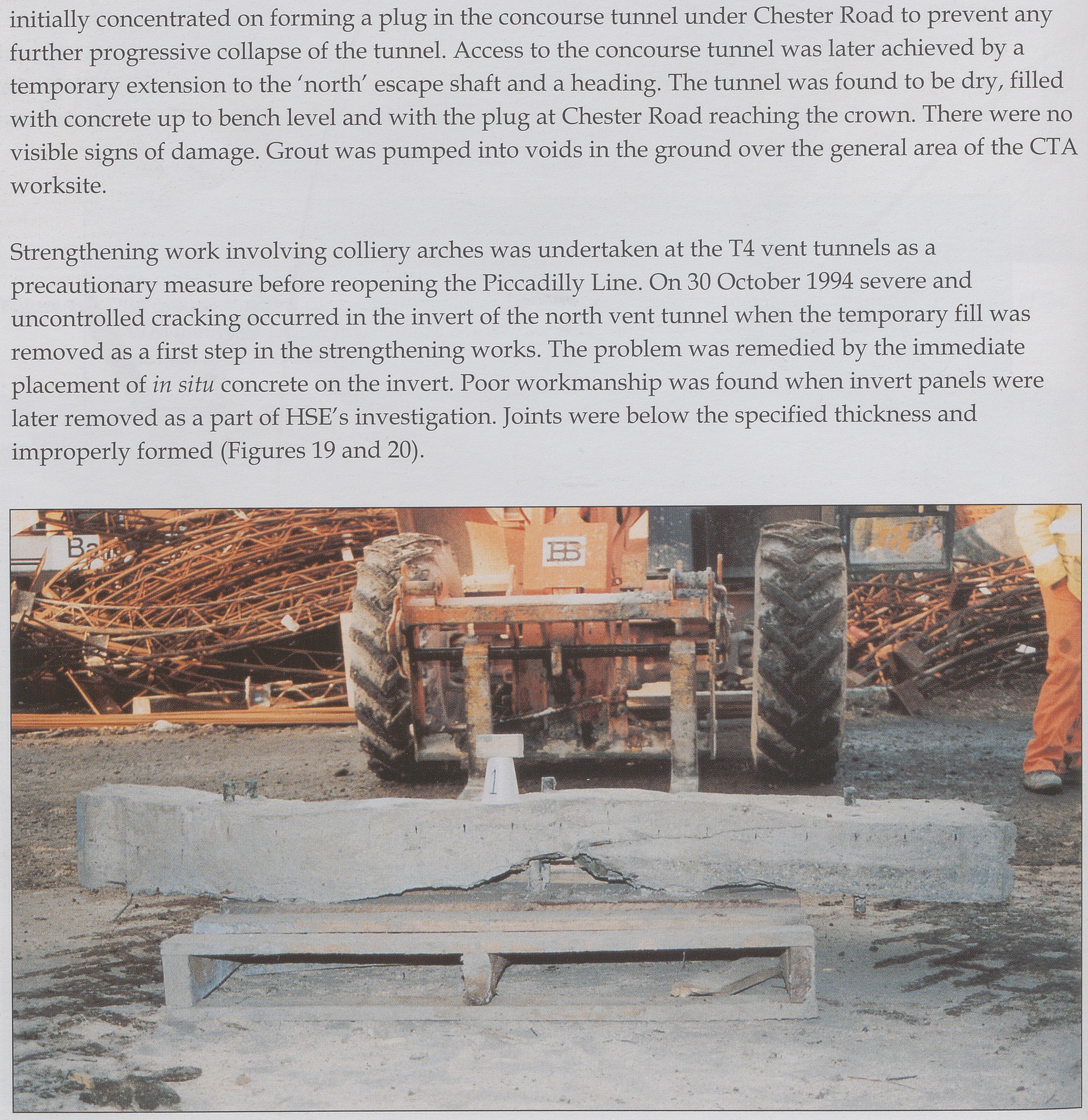


Figure 19 *Invert panel recovered from T4 NATM works. Invert panel from the NVT. The joint is below the specified thickness and improperly formed*

Figure 20 *Invert panel recovered from T4 NATM works. Invert panel from the NVT. The opposing sides of the joint are over and under thickness, faces do not abut on the flat and there is no reinforcement continuity across the joint. The two parts of the invert broke apart during recovery*

207 Other panels taken from T4 showed similar problems and lamination caused by inclusion of rebound material. Further T4 defects were found by visual inspection. There was evidence of:

- exposed mesh in the surface of the shotcrete;
- thin sections of shotcrete; and
- inclusion of rebound material in the structure.

208 The recovery plan for CTA involved the construction of a large circular shaft that enveloped the disturbed ground. It was three times the diameter of the original shaft and took nearly two years to design and construct. Two smaller access shafts were also constructed. The CTA station tunnels were variously rebuilt with concrete and cast iron segmental linings. Both were installed using shields. Further NATM work was restricted to the formation of a cross-over and some turnouts in undisturbed ground. The T4 station was completed in NATM to a revised design that aided buildability. In particular, lattice girders were provided around the full tunnel circumferences, the tunnel cross-sections were changed to increase the curvature of the inverts, the temporary central walls (and, hence, the invert joints) were omitted, and the platform tunnels were constructed sequentially and permanently lined before work started on the concourse tunnel. Systems for managing the project, in particular its supervision and monitoring, were radically changed and involved a close partnering arrangement between the client and contractor. The settlement of structures and the surface was contained within fine tolerances and was an indicator of the success achieved in subsequent NATM construction.

209 The cost of the recovery work was of the order of £150 million, around three times the original value of Balfour Beatty's work. The opening of the Heathrow Express Rail Link was delayed six months until June 1998.

HSE investigation and related actions

Initial considerations

210 HSE inspectors visited site on Friday 21 October 1994. It was clear that the investigation would be a major task requiring the assembly of an expert team. Inspectors were drawn from HSE's Field Operations Directorate, Railways Inspectorate and Directorate of Science and Technology. This was supplemented by tunnelling expertise from WS Atkins, consultants retained by HSE. Administrative support was drawn from HSE's HQ.

211 Other NATM work in London clay was under way at a baggage transfer tunnel linking CTA to T4 and at two major contracts on the Jubilee Line Extension Project in central London. Immediately after the collapse all projects voluntarily suspended NATM work as a precautionary measure. HSE requested that NATM work should not recommence until the project teams were able to demonstrate that they could adequately control the risks to the workforce and the public.

212 The Health and Safety Commission (HSC) requested HSE to carry out a two-part investigation. Mr M S Nattrass, CBE, HM Chief Inspector of Construction, was asked to lead. HSE was asked:

- first, to consider whether there were any broader health and safety implications concerning the construction of NATM tunnels in the UK, and the safety of finished tunnels using this method when compared to tunnels constructed using different tunnelling techniques;
- second, to investigate the causes of the Heathrow collapse and publish a report of the findings.

213 HSE set up a Project Board with independent members to oversee HSE's work (see Appendix 9).

Dealing with the safety of NATM

214 To assist the industry, HSE published an early discussion paper entitled *The use of NATM in soft ground in the UK* on 5 December 1994,[9] sponsored a meeting held at the Institution of Civil Engineers on 25 January 1995 (reported in the *Proceedings of the Institution of Civil Engineers*[10]) and engaged in extensive discussions with those wishing to recommence NATM work.

215 In response to the first limb of HSC's request, HSE published the NATM Report on 9 May 1996.[1]

216 HSE additionally commissioned a research report from Dr C P M Snee of Bradford University into post-construction auditing. That work has been separately published by HSE as a contract research report.[11]

Dealing with other NATM projects

217 HSE received over 30 NATM proposals, ranging from small-scale to the substantial, for restarting NATM work. Except for the smallest and simplest jobs, HSE found there were at the outset significant

deficiencies in the proposals. Some technical aspects of NATM design and construction were poorly understood, in particular heading stability including both the excavated face and the incomplete lining, and the possible effects of compensation grouting. HSE found that it was possible to satisfactorily resolve such issues through the goodwill and efforts of those involved in further discussions and on-site verification. Further details are given in the NATM Report.[1]

The Heathrow investigation

218 HSE established an on-site office from which to carry forward the investigation. Over 100 people were subsequently interviewed and a substantial volume of documentary evidence was collected. The assembly of factual evidence was complicated by the extended period over which the project had developed from inception to collapse, the various 24 h shift systems worked by the parties during construction, the number of parties and people involved and the disruption, including the loss of papers, caused by the destruction of Camborne House which had been used as offices by the CTA team.

219 The surviving NATM works at T4 were subjected to close scrutiny and a number of large shotcrete panels were cut out and lifted from the inverts of those tunnels for close inspection (Figures 19 and 20).

220 The novel use of NATM with compensation grouting in London clay created considerable challenges in the technical review of the designs and construction techniques.

221 Investigation of the site's geology found that there were no unusual geological conditions that could have accounted for the collapse. In particular:

- there was no recent history of significant disturbance to the ground through human activity;
- there was no evidence to suggest that the London clay formation was other than typical and thus, barring the presence of major disturbances, was an ideal medium for tunnelling;
- only minor actual or potential disturbances of the London clay formation were identified at the site, namely:
  - a minor fault encountered in the enlargement of the concourse tunnel near the south escape shaft (at about ch. 98) found on 19 August 1994 and dipping at around 45° across the tunnel face. The feature was well clear of the eventual area of collapse and had no reported influence on construction;
  - a sub-horizontal shear situated above the crown of the concourse tunnel, also near the south escape shaft and well clear of the area of collapse, found during investigative boring subsequent to the collapse. Such a shear was unlikely to have significantly influenced the works.

222 Information about the progress made during construction was assembled and is shown at Appendix 2. The inability to visit and examine the seat of the initial collapse until the CTA site was excavated as a part of the recovery works in the summer of 1996 further complicated the investigation. BAA arranged for an independent specialist to make a highly detailed log of the ground and the crushed tunnel linings during excavation of the 60 m diameter caisson. Their factual report and completed log

became available at the end of 1996 and, among other matters, it showed that contamination of the clay by aviation fuel was minimal. Access to the seat of the collapse under Camborne House was not possible until the summer of 1997 when further tunnelling work passed through the affected zone.

Legal proceedings

223 Following consideration of the evidence, Balfour Beatty and Geoconsult were informed during August 1997 of HSE's intention to instigate legal proceedings.

224 At the Central Criminal Court (the Old Bailey) Balfour Beatty pleaded guilty to alleged breaches of sections 2(1) and 3(1) of the Health and Safety at Work etc Act 1974 (HSW Act)[2] concerning failure to ensure the safety of its employees during construction of the tunnels and, similarly, other people, as a part of its undertaking in designing and constructing the tunnels at the CTA. The Crown took the decision not to pursue similar allegations concerning T4 in the light of guilty pleas to the CTA offences and offered no evidence on these. 'Not guilty' verdicts were returned on T4 as a consequence.

225 Geoconsult pleaded not guilty to alleged breaches under the same provisions concerning failure to ensure the safety of its employees during construction of the tunnels and, similarly, other people, as a part of its undertaking in designing and providing technical supervision during the construction of the tunnels both at CTA and at T4. In view of the decision taken concerning Balfour Beatty and T4, the Crown decided it would be inappropriate to proceed further with the T4 allegations. 'Not guilty' verdicts were returned on T4 as a consequence. The jury returned unanimous guilty verdicts on the breaches at the CTA at the conclusion of Geoconsult's trial. The trial judge said that Geoconsult's culpability was confined to aspects of design monitoring and interpretation of monitoring of the NATM tunnelling - and to a failure to warn.

226 On 15 February 1999, Balfour Beatty was fined £1.2 million, at that time the biggest single fine for an offence under the HSW Act. Geoconsult was fined £0.5 million. Both were ordered to pay contributions of £100 000 towards the prosecution's costs. Balfour Beatty was given credit, by a reduction in the fine, for its timely guilty pleas and both parties were similarly credited for the exemplary steps they took post collapse.

227 On 30 July 1999, the Court of Appeal considered and dismissed Geoconsult's application for leave to appeal against conviction. Likewise, the Court considered there were no grounds for changing the financial penalties imposed on the company.

The key findings

Culture of the industry

228 All tunnelling entails some uncertainty. The objective of those embarking on tunnelling projects should be to ensure that uncertainty does not lead to unacceptable levels of risk. Prior to the collapse, most people were unaware of previous NATM failures and many were attracted to the apparent economies of NATM, a feature strongly advanced by proponents of the technique. A cultural mind-set focused attention on the apparent economies rather than the particular risks. HSE's involvement with those wishing to restart other NATM work showed that this project was far from alone.

New Austrian Tunnelling Method

229 The NATM Report[1] put into the public domain a comprehensive review of the process, worldwide collapses and the principles that should be followed to ensure safety. The report contained 21 principal conclusions. These are reproduced at Appendix 5 to this report. Readers seeking further information are directed to the full NATM report.[1]

Heathrow

230 The Heathrow collapses could have been prevented if the parties had taken reasonably practicable steps. Instead, there was a lack of engineering control and, most importantly, there was a lack of safety management. (See the NATM Report,[1] Principal conclusion 16: 'NATM tunnels require the deployment of considerable skill and care in investigation, planning, design, construction and monitoring. Clients, designers and constructors should not underestimate the complexity of the task they will face before and during construction.')

231 Hazards were significant. The tunnels were below the world's busiest international airport and there was enormous potential for harm. In particular, the Piccadilly Line tunnels were especially vulnerable by reason of their construction. They were formed from unbolted precast concrete segments. While entirely safe in normal circumstances, nearby tunnelling created a risk. In addition, there was a risk of derailment in the event of large-scale ground movements.

232 Both at CTA and T4, three parallel and closely spaced NATM tunnels were under construction in contrast to the single trial tunnel. Apart from that trial, these were the first NATM tunnels in London clay. Risks inherent with the choice of NATM arose from the consequences of falling ground at the unsupported excavated faces and from a failure to properly construct the *in situ* shell linings. The possibility of major collapses was foreseeable. In addition, compensation grouting was being used for the first time in London clay and the potential impact on NATM was unknown.

233 From the early stages of the Heathrow project through to final collapse, there were failures to demonstrate the necessary level of care and serious errors were made. There were failures to deal

adequately with risks to people from a major collapse. There were deficiencies in identifying hazards and consequences, and in the management of risk. As a consequence, errors were made leading to poor design and planning, a lack of quality during construction, a lack of engineering control and, most importantly, a lack of safety management. The collapse could have been prevented. Warnings of its approach were present from an early stage; but quests for economy and progress were given higher priority.

234 If further warning was required, the disastrous and fatal NATM collapse in Munich one month to the day before the Heathrow event should have alerted the parties.

235 HSE's investigation found that the incident had all the hallmarks of an 'organisational accident'; that is, a multiplicity of causes led to the position where systems, variously used by the client, designers and contractors, were unequal to the challenge and failed. A major accident adversely affecting the safety of a large number of people occurred. On the day of the collapse, workers in the tunnels and on the surface were seriously at risk. Others outside the boundary of the site, especially those using the Piccadilly Line, were also at risk. Similar hazards were poorly controlled at other places where NATM was in use.

236 There were undoubtedly human errors; but these were merely a consequence of foreseeable cultural, organisational and management failures. The causes of the incident were rooted in failures in 'defensive' systems (ie preventative management systems) that did not adequately deal with hazard identification, risk avoidance and reduction, and the control of the remaining residual risks. There was organisational blindness to the possibility of collapse. As a consequence, human failures were not readily identified and corrected; and mistakes in decision-making were more likely.

237 Thus:

- hazards arising from the *in situ* construction of thin shell linings and the complementary use of compensation grouting were not identified by all parties;
- risk was not avoided and reduced through the contractual arrangements, the design of the permanent works and the NATM design;
- the remaining residual risks were not controlled during construction through the 'defensive' systems used by the parties;
- the particular risks associated with remedial work were not recognised.

238 The direct cause of the tunnel collapses was a chain of events involving:

- substandard construction in the initial length of the CTA concourse tunnel over a period of some three months;
- grout jacking that damaged the same length of tunnel and inadequately executed repairs to it some two months before the collapse;
- the construction of the down-line platform tunnel in failing ground;
- major structural failure in the concourse and down-line tunnels, progressive failure in the adjacent ground, and further badly executed repairs during October 1994.

239 There were weaknesses in contingency and emergency procedures.

240 Other NATM work at the project was similarly unsatisfactory as a consequence of the same underlying organisational failures. This was exemplified by:

- the failure to construct the NATM lining elsewhere to the correct profile, thickness and sequence;
- defective invert construction elsewhere as demonstrated by sample panels cut out at T4 after the collapse;
- the discovery of substantially underthick lining on 9 October in the T4 south vent tunnel; and
- the failure of the invert to the T4 north vent tunnel on 30 October during remedial strengthening work.

241 Paragraphs 242-298 provide further information. A simplified technical account of the CTA collapse mechanism is given at Appendix 4.

Results of the investigation

242 This section of the report provides more detailed information about HSE's key findings.

Hazard identification

243 Hazards arising from the *in situ* construction of thin shell linings and the complementary use of compensation grouting were not identified. (See the NATM Report,[1] Principal conclusion 1: 'Major NATM collapses have occurred world-wide. This finding and recent scrutiny of proposals for NATM in the UK leads HSE to conclude that some safety critical aspects of NATM design and construction have been poorly understood, and past experience has not been adequately taken into account.')

244 The potential for collapse of the NATM tunnels created a major hazard to the safety of those working in the tunnels and to members of the public, the infrastructure, the built environment and to the operation of the airport. (See the NATM Report,[1] Principal conclusion 2: 'NATM tunnel collapses in urban areas can result in major consequences not just to those working in the tunnel but to members of the public, the infrastructure and the built environment.')

245 During 1991, broadly based project risk analyses by the client's team identified that NATM in London clay and the use of compensation grouting in conjunction with it were untried methods. They further identified that the supervision of the tunnelling works other than by the client's designer could result in problems on site. The NATM risk analysis specifically identified health and safety as an issue. The trial tunnel was identified as a partial solution. However, this only dealt with 'proving' NATM and then only for a single tunnel arrangement without the concomitant use of compensation grouting. Moreover, design and construction supervision for the trial tunnel were by the client team rather than the contractor. This meant that the trial did not explore the possible difficulties of passing NATM design and self-certificated supervision to a contractor, the approach subsequently adopted.

246 BAA's risk analysis did not sufficiently emphasise the possibilities of a major collapse and the issue was given insufficient attention. By the time of the collapse, BAA's senior management had little appreciation of the hazard and did not consider such an event credible.

247 Balfour Beatty's hazard analyses only dealt with low-level operational matters and not the more strategic matters. Hence key points concerning the safe completion of the work were not identified.

Risk avoidance and risk reduction

248 Risk was not avoided and reduced through the contractual arrangements, the design of the permanent works and the NATM design. (See the NATM Report,[1] Principal conclusion 4: 'There is always some degree of uncertainty in tunnelling design and construction. A risk-based approach to design and management is required.')

The contract

249 The contractual arrangements involving the assignment to the contractor of the process risks from NATM and settlement control, the self-certification of quality and the separation of the design of the permanent and NATM works meant that the parties had to deal with a number of significant issues.

250 The chosen approach substantially transferred the process risks connected with the use of new technologies from the client to the contractor and this limited the opportunities for direct intervention by the client team.

251 To some degree there was a contradiction in the contractual approach. The client chose to let the contract through a traditional competitive tender but had the expectation that self-certification, a cutting-edge approach more closely aligned with new forms of contracting, would provide for quality.

252 Likewise, the advantages accruing from greater integration of the temporary and permanent works design were lost. The contractual arrangements meant that the two designs were separately developed by the two design teams.

Permanent works design

253 Breaking the link between the design of the permanent and temporary (ie NATM) works created difficulties in taking an integrated design approach to risk reduction. The separation reduced the permanent works designer's interest in the impact that the permanent works had on the temporary works; and, likewise, it limited the temporary works designer's ability to influence the permanent design. (See the NATM Report,[1] Principal conclusion 9: 'An integrated approach should be taken to the design of permanent and temporary works. Design should consider the whole process of NATM tunnel construction.' See also the full text of that report for further explanation.)

254 For instance, at T4 the station was sited directly under a car park, a London Underground station and other public areas that were to remain in use during construction. At one point, a large cavern at a shallow depth was required to accommodate the client's permanent works. Some tenderers picked up the considerable difficulty this would create, offered alternative designs for the permanent works and allowed for the increased cost. Balfour Beatty came to appreciate the problem post tender and offered a late redesign at considerable expense to itself. The contractor had to cover the client's additional costs for redesigning the permanent works in addition to their own.

255 Likewise, the flattened invert profile of the platform and concourse tunnels met the client's needs but created difficulties for the NATM designer and contractor.

NATM design

256 The NATM design could have been safely constructed but the margin for error during construction was small. A robust design was essential but it was not provided. (See the NATM Report,[1] Principal conclusion 7: 'A robust design is essential. Design for each element should be fully developed before

construction of that element commences. Design modifications should only be used to enhance a robust design.)'

257 Safety critical aspects of NATM design and construction were poorly understood. This extended to buildability issues, especially of the invert and the invert joint, the selection and use of compensation grouting to control settlement, necessary supervision and monitoring, and training about safety-critical features of NATM.

258 Geoconsult should have come to a more satisfactory understanding of the prevailing ground conditions, and should have taken them into account when using computer-based modelling tools. It is apparent that they failed to have a full understanding of the published properties of London clay. They adopted a low safety factor for their design. The flattened invert profile reduced the construction costs but made it more susceptible to failure, especially if improperly constructed. The invert joint was sited at a critical location and, crucially, the detail suffered from a lack of buildability. (See the NATM Report,[1] Principal conclusion 13: 'Buildability should be considered in design and construction planning.') Unlike similar work at the trial tunnel, metal lattice girders were omitted from the benches and inverts. The inclusion of lattice girders would have provided a 'fail-to-safety' feature during construction by providing a visual indicator of mistakes in profile, shotcrete thickness and continuity in the lining. Their omission meant that construction was more likely to 'fail-to-danger' since construction errors were liable to pass undetected. A more robust design could have been developed. It was an essential safety feature.

259 Safety of the completed NATM linings was highly dependent on monitoring and data interpretation. (See the NATM Report,[1] Principal conclusion 11: 'The safety of completed sprayed concrete linings depends on monitoring and data interpretation.') The design economies meant that greater care was needed during construction and monitoring. However, the design did not fully specify what monitoring regime was required nor set out predefined trigger levels and the design did not fully consider what contingency actions might be required to secure continued stability in the event of difficulties during construction.

Control of residual risks

260 Residual risks, that is those risks remaining after design work had been completed, were not controlled during construction by the management and the health and safety systems used by the parties.

The client

261 By assigning the choice and control of NATM to the contractor, BAA lost the ability to directly influence the work and to play an active part in the associated instrument-based monitoring regime. BAA chose to oversee the construction work indirectly through a system of infrequent audits. These proved ineffectual. The untimely reorganisation of their supervisory team just as site work commenced was unhelpful.

262 BAA's decision that they required staff competent in auditing rather than knowledgeable in

tunnelling, further reduced their abilities to influence the work. BAA's management systems failed to challenge the contractor sufficiently robustly on safety-critical issues, in particular the quality and integrity of the CTA concourse tunnel. Senior management failed to have sufficient regard to disquiet expressed by middle and junior management. High-level expressions of commitment proved ineffective.

The principal/main contractor and specialist subcontractor

Planning

263 The risk of major collapse was not adequately addressed by Balfour Beatty during planning, design and construction. Risks from the possibility of major collapses were not identified by hazard and risk analyses carried out at each worksite and for each operation. These concentrated on routine hazards to individual workers. They did not take a more strategic view of risk reduction. Hence measures, which are now better understood, such as buildability reviews and the provision of robust multi-layered 'defensive' systems designed to reduce the likelihood of human errors and contain those which occurred, were not developed. There was a failure to appreciate the safety significance of monitoring. Contingency plans were not prepared. Emergency procedures were deficient when called upon to deal with the immediate consequences at the time of the collapse.

Initial training

264 Balfour Beatty failed to create the safety culture and attitudinal changes required to ensure safety under the working methods that were adopted. Initial training failed to drive home a full appreciation of the safety issues surrounding the *in situ* construction of thin shell linings.

265 Training in self-certification was ineffective. Only limited numbers of managers and engineers attended. The substantial cultural changes required to operate such a system were not fully taken on board. Once work commenced, opportunities for bringing about changes were inevitably reduced.

Work practices and quality

266 Quality was essential for the successful completion of the NATM work. (See the NATM Report,[1] Principal conclusion 12: 'The achievement of quality is essential if a NATM project is to be completed successfully.') However, work practices and self-certification systems did not deliver the quality required. Problems in mixing and delivering shotcrete led to the use of poor quality material. There was a lack of care during formation of the linings. The consequences were manifold. Linings were under thickness, under strength and, consequently, less able to support the ground. The construction of the flattened inverts proved particularly difficult. Misshapen tunnels attracted higher loadings, suffered load concentrations and did not behave in the manner expected by the design. Laminations caused by the inclusion of rebound material introduced planes of weakness.

267 No sampling cores had been taken from the invert shotcrete during construction. Instead, they had mostly been taken from the more accessible benches where better quality shotcrete was more likely to be present. About 40% of the shotcrete samples recovered during the re-excavation of the CTA

indicated that the NATM lining was under thickness. Some 28% had compressive strengths less than the specification. A significant number of samples could not be tested; they were so weak that they broke up during recovery. Some shotcrete could readily be taken apart by hand due to insufficient cement binder.

268 After the CTA collapse, inspection at T4 found similar problems. In one place, the wall of the south vent tunnel was only 50 mm rather than 300 mm thick and lacked cement binder. Likewise, this tunnel was grossly oversized and misshapen. Panels removed from T4 inverts exposed linings that were too thin and horizontally laminated due to the presence of 'rebound' material (see Figures 19 and 20).

Monitoring

269 Instrument-based performance monitoring of the lining was ineffective. The function was inadequately resourced and was poorly performed. Convergence from an early stage in the walls of the CTA concourse tunnel went unnoticed, the extent of the damage to that tunnel during August was not identified and there were further interpretation failures in the run-up to the collapse. Geoconsult did not keep in touch with the work on site due to a failure to provide sufficient resources and a failure to prioritise.

270 Monitoring was not accorded sufficient attention by Balfour Beatty's engineering team. There was a failure to integrate information from the several quality and instrument monitoring systems and a failure to link the well-documented history of poor workmanship with evidence of continuing movements in the concourse tunnel lining.

Process management

271 Management systems were unsatisfactory. There was an imbalance between the production systems and the 'defensive' systems for monitoring quality and the performance of the lining. Production and quality management had been delegated to the same people in a number of management teams variously located throughout the project. In the last resort the 'defensive' systems were overseen by the lightly staffed and centrally located engineering team but it exerted little effective influence. Indicative of this was the four-month delay in correcting the quality system to provide 'hold' points where timely checks could be made before shotcreting. Even then the quality system was not effective in testing the lining against the designer's specification and the failure to routinely test the invert was a major error. Self-certification need not be inherently unsafe; but a full regard must be paid to the potential pitfalls when developing and implementing such quality systems as a part of the control strategy (see the NATM Report[1]).

272 The delegation of production and quality management to the same people increased the likelihood of failure. Defective engineering and management systems, and the way they were operated, led people to concentrate on progress to the detriment of quality. Insufficient consideration was given to the safety risks from defective tunnels despite clear evidence of poor workmanship. There were wide-ranging failures. These included:

- the agreement with Geoconsult to restrict their resources at the project;
- the failure to have readily available NATM engineering expertise round the clock and the 'out-of-hours' communications difficulties concerning Geoconsult's site engineer;
- the failure to prevent damage to in-tunnel survey points and delays in their replacement;
- inadequate systems for handling monitoring data;
- failure to establish systems for the structured review of quality and monitoring information;
- the reliance on a single person whose views were not subject to peer review for the crucial NATM monitoring role;
- giving insufficient weight to the advice received from Geoconsult;
- not identifying the significance of poor workmanship and the potential consequences;
- not controlling compensation grouting at Camborne House and not managing the consequences;
- not investigating the structural integrity of the CTA concourse tunnel and the ground before commencing the two CTA platform tunnels;
- not identifying the potential consequences of constructing the three parallel tunnels at the same time;
- not responding satisfactorily to BAA's letter of 2 September 1994 questioning the structural integrity of the concourse tunnel;
- not securing the successful conclusion of lining repairs.

273 There was a failure to involve workers sufficiently in health and safety issues. NATM problems were well-known to junior engineers and people at the work face who could have volunteered advice about the difficulties they were facing. However, there were no effective arrangements through which such views could be channelled.

Risk during remedial work

274 The particular risks associated with remedial work were not recognised.

275 Remedial work is particularly prone to the risk of errors due to organisational and human failures. Errors were made more likely by:

- unpreparedness for the unplanned;
- the failure to have in place, or the failure to follow, procedures tailored to deal with the non-routine; and
- pressures to minimise lost production.

Repairs were permitted without sufficient inspection, engineering analysis and design, and without recording and certificating the repair work that was completed. The unsatisfactory conduct of remedial works to the CTA concourse tunnel in August, to the T4 south vent tunnel in October, and at CTA shortly before the collapse, demonstrate the ease with which such errors can be made and remain undetected in the absence of suitable management control systems.

276 Had the seriousness of the situation been understood and the safety of those in the tunnel and of everyone on the surface including the public been considered, the following steps should have been taken before the October repairs.

- A full engineering review should have been made to determine why the lining was behaving as it did. This should have been carried out some time earlier when it was first clear that there was a serious and developing problem.
- A considered engineering plan and related method statements should have been developed for the remedial works. Risk assessment would be central to these processes.
- The plan should then have been explained to those carrying it out.
- Such a plan should have included:
  - alerting the airport managers and other parties with safety-related interests;
  - the immediate closing down of all nearby tunnelling activities and securing their stability;
  - the planned removal and the replacement of limited lengths of fill for the purpose of inspection to determine the full extent of repairs;
  - similar removal and replacement so that repairs could be made and the shotcrete permitted to gain sufficient strength before further repairs were made nearby. One possible remedial measure could have involved the casting of additional rapid hardening concrete on the damaged invert and keying into it. This would have quickly added to the strength of the weakened invert. This concrete might then have been used as part of the permanent lining. (As the strength of the temporary lining was not taken into account in the finished tunnel design there was no absolute need to remove the defective NATM lining except where it had encroached excessively into the zone designated for the permanent lining and for the purposes of making keying connections as a part of the remedial work);
  - supervision of the work by experienced engineers with close oversight by senior engineers;
  - round-the-clock monitoring of key factors such as:
    - convergence in the tunnel walls;
    - further movement at depth in the clay (eg by extensometers);
    - surveying for surface movements;
  - regular formal reviews of the work in hand, the monitoring information, and the safety procedures, by senior engineers and managers to ensure continuing safety;
  - the detailed recording of what was found and the work that was done to aid further engineering analysis.

Substandard construction

277 Repetitive construction defects in the CTA concourse tunnel made it unsound from the outset. Problems were known but not effectively addressed.

288 The lack of preparedness at the outset meant that people had to learn on the job and develop practices as the work proceeded. Unsatisfactory work practices in the formation of the invert, failures in the quality systems and failures in the interpretation of the instrument-based monitoring systems meant that serious defects occurred, and went undetected and uncorrected.

The consequences of compensation grouting/grout jacking

279 Damage to the CTA concourse tunnel was exacerbated by grout jacking. The consequences of using the compensation grouting equipment for a different process, ie grout jacking, were not taken into account. The high-pressure injection of grout put considerable forces into the ground. These forces,

and their potential effects on the tunnels, were not sufficiently understood.

280 There was a failure to co-ordinate the NATM construction and the grouting beneath Camborne House. Geoconsult was not represented at daily grouting assessment meetings but did receive copies of the minutes. No consideration was given to additional precautionary tunnel monitoring until visible signs of tunnel failure were apparent. Grout jacking had induced extra loading on the poorly constructed tunnel lining in the vicinity of Camborne House. Although this failure was not of a type to lead to immediate safety problems, there was an unacceptable increase in the level of risk.

281 Analysis of the August event was poor. It should have been starkly obvious that invert failure had occurred to either side of the grouting under Camborne House. Instructions for investigation and repair were inadequate. The production team was left to complete the task without the benefit of oversight by the engineering team. Opportunities for the engineering team to view and further assess the inadequate lining were lost. Repairs were not made to the damaged invert towards the fuel depot shaft.

Construction of the down-line platform tunnel in failing ground

282 The down-line platform tunnel was constructed into failing ground.

283 A considered interpretation of the data prior to the start of the platform drives to the north should have concluded that the concourse tunnel lining was unsound. There was increased surface settlement, ever-increasing chord strains, and extensometers were showing large ground strains. Data from ch. 23, 30 and 41 showed that the lining was failing to adequately support the ground. The additional tunnel drives increased the risk to the concourse tunnel. They were likely to cause further ground movements, so inducing additional deformations into the sheared clay at the concourse tunnel. The problems were compounded by synchronous construction of the platform tunnels rather than in echelon as designed.

284 Tunnelling continued despite the observation of 'soft ground' by the project director shortly after the start of the first platform tunnel. Further ground investigations should have been carried out. (See the NATM Report,[1] Principal conclusion 6: 'Ground investigations throughout must ensure that there is no likelihood of meeting unexpected conditions of a critical nature.') However, nothing was done to consider why the ground conditions might have changed, to review the design and detailing, or to change the construction methods. This exemplified the imbalance between the competing demands of production and 'defensive' systems.

Major failure in the concourse tunnel, the down-line tunnel and the juxtaposed ground; and further poorly executed repairs

285 Inadequacies in the monitoring systems meant that further damage to the concourse tunnel invert associated with the formation of the down-line platform tunnel 'north' was only discovered at a late stage. The lack of adequate contingency plans for remedial work exacerbated the position and contributed to the developing collapse.

286 In the ten-day period before invert repairs commenced, monitoring data were indicating approaching lining failure unless additional support was provided. Repair work was started without proper engineering investigation, analysis, design, instruction and oversight. It is not surprising that the inexperienced production team went about the repairs in an uncontrolled manner.

287 As a result, the first 30 m of the concourse tunnel invert, which was already weak, was further weakened by the ad hoc repairs and continued tunnelling for the down-line platform tunnel 'north'. Eventually, the position became irrecoverable and collapse became inevitable.

The collapse

288 Balfour Beatty failed to ensure safety on the last night shift.

289 Many of Balfour Beatty's engineers lacked NATM experience and this was particularly apparent on the last night. None of that shift's supervisory staff had any previous site experience of NATM before joining the project. The consequences went unforeseen and an inexperienced team was unequal to the task.

290 As NATM requires the integration of design and construction, it was important that staff experienced in both facets were available. Moreover, as senior staff normally work day shifts, it is good practice for experienced shift staff at other levels to work nights as a counterbalance. It is clear from their lack of experience and their subsequent actions that staff on shift were unequal for the demands made of them. This placed everybody's safety at risk.

291 There was no effective engineering control over the concourse tunnel repairs. This led to the removal of a sound section of the invert simply because it was too high, and the removal of a further sound section adjacent to a major wall crack simply because a workman was at a loose end. These examples are symptomatic of ad hoc decision-making throughout the shift.

292 By 22.30 h the down-line platform tunnel 'north' drive heading was visibly failing. Cracks were appearing at the face and along the walls. People were unnecessarily exposed to very high risks to their safety. It should have been evident that collapse was inevitable and that instructions for the urgent evacuation of the whole of the CTA works were necessary.

293 However, the gangs were kept underground even when the section agent and the 'NATM engineer' were sufficiently concerned that they left site to collect the works manager and Geoconsult's site engineer. Employees were placed at unnecessary and grossly excessive risk for something of the order of two and a quarter hours. The tunnels could have suddenly failed at any time during this period. In the event, not only were people exposed to this risk, but they were also further exposed during evacuation to risks from the collapsing ground when they were at the surface.

Failures in contingency and emergency procedures

294 There were failures in the contingency and emergency procedures. (See the NATM Report,[1] Principal conclusion 14: 'Contingency plans and emergency procedures are required to deal with adverse events.')

295 Suitable contingency plans and emergency procedures had not been developed for the project and so could not be put into effect. This was a consequence of inadequate hazard identification and risk assessment. There were no contingency plans to reduce the likelihood of failure. Emergency plans were restricted to the evacuation of work people from the site.

296 There was a failure to ensure the safety of others using the airport. The airport authorities were not informed at the earliest opportunity. Instead, they were told only after the collapse had happened. This meant that timely precautionary measures, such as cordoning off those parts of the infrastructure at risk and informing London Underground, were impossible.

297 Once the CTA tunnel collapse had started, it was not possible to predict the full extent of the inevitable disturbance with any certainty, nor the manner in which it would propagate and progress. It could not be assumed that the collapse would be limited in area and to a particular tunnel. All surface and subsurface facilities in the vicinity of the tunnel complex were at immediate risk. Likewise, the Piccadilly Line.

298 The likelihood of sudden collapse lessened as time passed. The decision to fill the surviving CTA tunnels with foamed concrete to stabilise them and to protect car parks 1A and 3 and the Piccadilly Line reduced risks from further collapse.

Lessons from the incident

Major accident potential in construction

299 Major accident hazards are manifested in events that have a low probability of occurring, but when they do, they have considerable consequences for those affected. By their very nature they tend to be sufficiently infrequent that the potential for such events can be easily overlooked. The Heathrow incident is a timely reminder that such accidents can and do adversely affect the construction industry.

300 Such accidents must be prevented through effective risk management. The industry cannot simply rely on good fortune. The potential for major accidents, whether due to the construction process or its close proximity to the public, must be recognised and controlled.

Hazard and consequence analysis, and risk assessment for new or unfamiliar technologies and public safety

301 Major hazards and the potential consequences associated with proposed construction processes should be identified as a first step by those involved in commissioning, planning, designing and construction. New or unfamiliar technologies require particular review, as do major projects with the potential to cause significant harm to workers or the public. Lessons from past major civil engineering failures highlight the point.

302 The incidents at Brent Cross in 1964 and at London's Upper Thames Street in 1991 when cranes fell onto nearby roads, illustrate the hazards connected with major projects close to the public. Collapses of box-girder bridges, such as in 1970 at Milford Haven and in Melbourne, Australia, are markers of the problems which can arise when new technologies are taken beyond acceptable limits. Like Heathrow, the latter incident provided lessons in organisational failures. Collapses associated with the rapid expansion in major falsework structures in the UK around 1970 provided lessons about contractors' temporary works.[12]

303 A track record from previous uses of a process can provide some indication of what might occur. The NATM report[1] highlighted the ability to readily identify the worldwide experience of NATM failures when direct UK experience was limited.

304 However, it is not sufficient merely to determine that a process has been used satisfactorily by others. The absence of a previous incident does not denote that a process is without risk. Likewise, it is not sufficient to use an overly simplistic and mechanistic approach to hazard and consequence analysis, and risk control, that focuses on general hazards while failing to address the particular process hazards. Rather, it is essential to fully understand and analyse a process - including risks present at intermediate stages of construction, from the design and construction of temporary works, and from the plant and equipment that will be used - if potential hazards are to be identified and the risks avoided or, where that is not possible, controlled. Organisational as well as technical factors should be considered.

305 Risk assessment should consider major hazard events which could affect workers and the public, and not simply risks to individuals at work. Risk assessment should be a fundamental step in the procedures adopted by all parties: it is inappropriate wholly to leave the control of risk to contractors. Identified risks can be communicated to others by preparing and making available project risk registers which can then be subject to continuing review. The NATM Report[1] provides further comprehensive advice about how risk can be managed where NATM is proposed.

Management systems and organisational and human factors

306 It is essential that organisational and human factors are taken into account when devising 'defensive' management systems to secure safety. (See the NATM Report,[1] Principal conclusion 15: 'NATM is heavily dependent on avoiding human failure.')

307 Organisations, and groups of organisations, have multiple defences to prevent incidents. In the construction industry these defences can be influenced by the contractual relationships and by the different hazard and risk identification methods and controls variously used by the parties. This has the advantage of providing some redundancy and diversity in the defences against failure but it can also provide the opportunity for misunderstandings and simultaneous failures where there is uncertainty about the respective roles and responsibilities of the parties. Cases in point may be new forms of contract where roles are poorly understood and new technologies where people variously rely on others to understand, communicate and control the risks.

308 Pressures for production are naturally present within an organisation. These must of necessity be balanced by precautionary measures that secure health and safety and, where safety is dependent on the product (eg the structure), that do so by achieving a quality product. Management structures and 'defensive' systems must successfully deal with conflict.

309 Remedial and maintenance activities are particularly vulnerable if organisational weaknesses exist. Such non-routine activities need to be well planned and managed. At the human level, tasks and error control measures should be designed to avoid the likelihood of failure and to detect any errors that do occur. Procedures that are inappropriate or poorly designed will be vulnerable to failure. HSE's NATM Report[1] provides further advice as does HSE's publication *Reducing error and influencing behaviour*.[13]

310 Management systems should create and maintain positive safety cultures which:

- demonstrate the commitment of senior managers;
- secure well-developed corporate awareness of key project risks;
- ensure that crucial information is brought to the attention of senior managers;
- ensure that key decisions are made at the right level and at the right time; and
- involve everyone at work including their safety representatives and enable them to make a full contribution.

A statutory framework for success

311 The Health and Safety at Work etc Act 1974[2] requires that duty holders, such as employers, protect people from risks arising from the duty holder's activities. The Management of Health and Safety at Work Regulations 1999 (MHSWR)[7] (replacing the earlier MHSWR 1992[7]) and the Construction (Design and Management) Regulations 1994 (CDM),[8] which had yet to come into effect at the time of the collapse, provide a framework of statutory measures for addressing major hazard events in the construction industry by requiring hazards to be identified and risks to be controlled.

312 MHSWR requires employers to take the first critical steps in identifying hazards and avoiding risks, or where that is not possible, reducing risks to an acceptable level. To secure health and safety, the Regulations require the creation of multi-layered defensive safety systems by planning, organising, controlling, monitoring and reviewing work activities, and by attention to co-ordination, co-operation, information, training and competence.

313 CDM addresses the practical application of these measures - by clients, designers, planning supervisors and contractors - in the context of construction projects through a framework that applies design and management solutions. (See the NATM Report,[1] Principal conclusion 20: 'The existing statutory provisions, and in particular CDM, provide a comprehensive system for the regulatory control of risk including the assessment of competences.') The duties on clients and designers, assisted by planning supervisors, variously secure the elimination of risk - or its reduction where that is not possible - by selecting competent duty holders, providing information, and, with particular regard to buildability, good specification and design. The duties placed on contractors direct them to the management of the remaining residual risks through planning, co-operation, consultation and control, and by involving workers.

314 CDM, the Safety Representatives and Safety Committees Regulations 1977[14] and, more recently, the Health and Safety (Consultation with Employees) Regulations 1996[15] provide a framework for actively involving workers.

315 Those involved in projects with the potential for major accidents should ensure that they have in place the culture, commitment, competence and health and safety management systems to secure the effective control of risk and the safe conclusion of the work. (See the NATM Report,[1] Principal conclusion 17: 'Competency of the NATM team is crucial, and should be assessed.')

316 Had such strategies been successfully adopted at the Heathrow Express Project, unnecessary risk, disruption, delay and cost would have been avoided. (See the NATM Report,[1] Principal conclusion 19: 'Provided careful account is taken of all the issues, it has proved possible for NATM work to proceed in safety.')

APPENDIX 1: Description of the construction processes and the ground

New Austrian Tunnelling Method

1 A comprehensive review of NATM is provided by HSE's report *Safety of New Austrian Tunnelling Method (NATM) tunnels* (the NATM Report).[1] This appendix provides a synopsis of some of the more important points relevant to this report.

2 The term NATM is widely used to describe a variety of similar tunnelling techniques which may have their origins in Austria but are by no means confined to it. The method has developed in a number of ways in various countries, most notably in Switzerland, Austria, Germany and Norway (where, in the latter instance, it is known as the Norwegian Method of Tunnelling). NATM has since been used in a range of ground conditions throughout the world with varying degrees of success in the early stages. The first use of NATM for shallow tunnels in soft ground in urban areas was in 1968 for the Frankfurt Metro, followed by Vienna and Munich. A daylight collapse occurred in Munich shortly before the Heathrow incident. A bus fell into the void and became lodged in waterlogged ground. There were three deaths involving people on the bus and a worker who tried unsuccessfully to warn them of the impending collapse. Thirty-six other passengers were injured. (Note: These figures revise information in the NATM Report which records the outcome as four fatalities and 27 injuries.)

3 Although slow when compared to TBM drives, NATM has the advantage that it does not require such a heavy capital outlay; and it can readily accommodate non-standard shapes required at intersections. In the UK, sprayed concrete linings have been used to support rock. NATM was used in chalk and gault clay in the construction of the Channel Tunnel. Further road tunnels in chalk were subsequently constructed. The lessons learnt had been published. In October 1989, Balfour Beatty printed an article in their in-house magazine noting the need to provide a high-quality concrete invert close behind the primary arch support when tunnelling in ground less favourable than competent rock.

The NATM construction technique in London clay

4 London clay, and its complexities, are described at paragraphs 34-38 of this appendix.

5 The introduction of NATM into London clay has been aided by increases in computing power and corresponding developments in analytical models such as finite-element analysis. The complexity of the calculations required to analyse the behaviour of the ground and the tunnel linings during multi-stage construction sequences had previously been impractical. The use of such computational models requires site-specific input parameters to be applied in an appropriate and consistent manner if the results are to be verifiable and reliable.

6 Three safety issues are paramount during the construction of NATM tunnels in London clay:

- the advancing face should be stable so that it does not collapse;
- the lining should be capable of supporting the ground during its incremental construction and thereafter; and
- there should be in place effective monitoring systems that ensure there is sufficient time for contingency and, where necessary, emergency plans to be satisfactorily completed in the event of adverse developments. This approach is encompassed within a 'Discovery-Recovery' model described in the NATM Report.[1]

7 The face must remain stable for sufficient time so that the lining can be constructed and the tunnel advanced. Clay has a property commonly referred to as its 'stand-up' time. The term relates to the ability of a face to be self-supporting due to the development of a reduced pore water pressure in the clay following excavation. It is a relatively short-lived effect after which time the ground will collapse. Importantly, the effect cannot always be relied upon due to geological variability such as naturally occurring planes of weakness, changing water content and inclusions. For safety, 'stand-up' times should be considered as 'fall-down' times and conservative values must be considered. The first sign of face instability typically occurs when a block falls from the face. A number of falling blocks may indicate a general instability. If not controlled, failure of one block may be followed by others and the collapse may enlarge to form a hole in the crown.

8 The cross-section of an advancing tunnel face may be divided horizontally into a number of smaller faces. There are typically three: the crown, bench and invert. This can be increased to six through vertical subdivision involving a twin heading and a temporary central wall (see Figures 21 and 22). The first heading, known as a side gallery, is constructed ahead of the second, the enlargement. A temporary wall constructed as part of the side gallery is progressively demolished either when a 2 m advance has been completed (as the designer specified at Heathrow) or as a step in each stage of forming the enlargement (as was actually done at Heathrow). Further subdivision can be achieved by introducing additional temporary crowns, walls and inverts.

9 Excavation is incrementally advanced in steps of about 1 m and to a predetermined sequence. In larger tunnels, the sequence is normally 'crown, bench, crown, bench, and double invert' on a working face and with the crown always in advance of the remainder, providing a stepped profile along the length of the tunnel. Shotcrete, a special concrete mix sprayed at high pressure, is used after each incremental excavation to form new panels to the lining. A 50 mm sealing layer is generally first applied to the excavated surface against which the new panel will be formed. At Heathrow, shotcrete was then applied in two layers, each reinforced by steel mesh to form a lining typically 200-300 mm thick. Subject to the design, the second layer can be applied before advancing the excavation or it may be delayed until a later stage in the cycle. Waste shotcrete in the form of loose cement-coated aggregate is known as 'rebound' because it normally arises from material rebounding during shotcreting. It adversely affects the quality of a lining if incorporated into it. Rebound should be treated as waste material and should be cleared from the work area. It is liable to collect in the lower recesses of bench panels and in inverts.

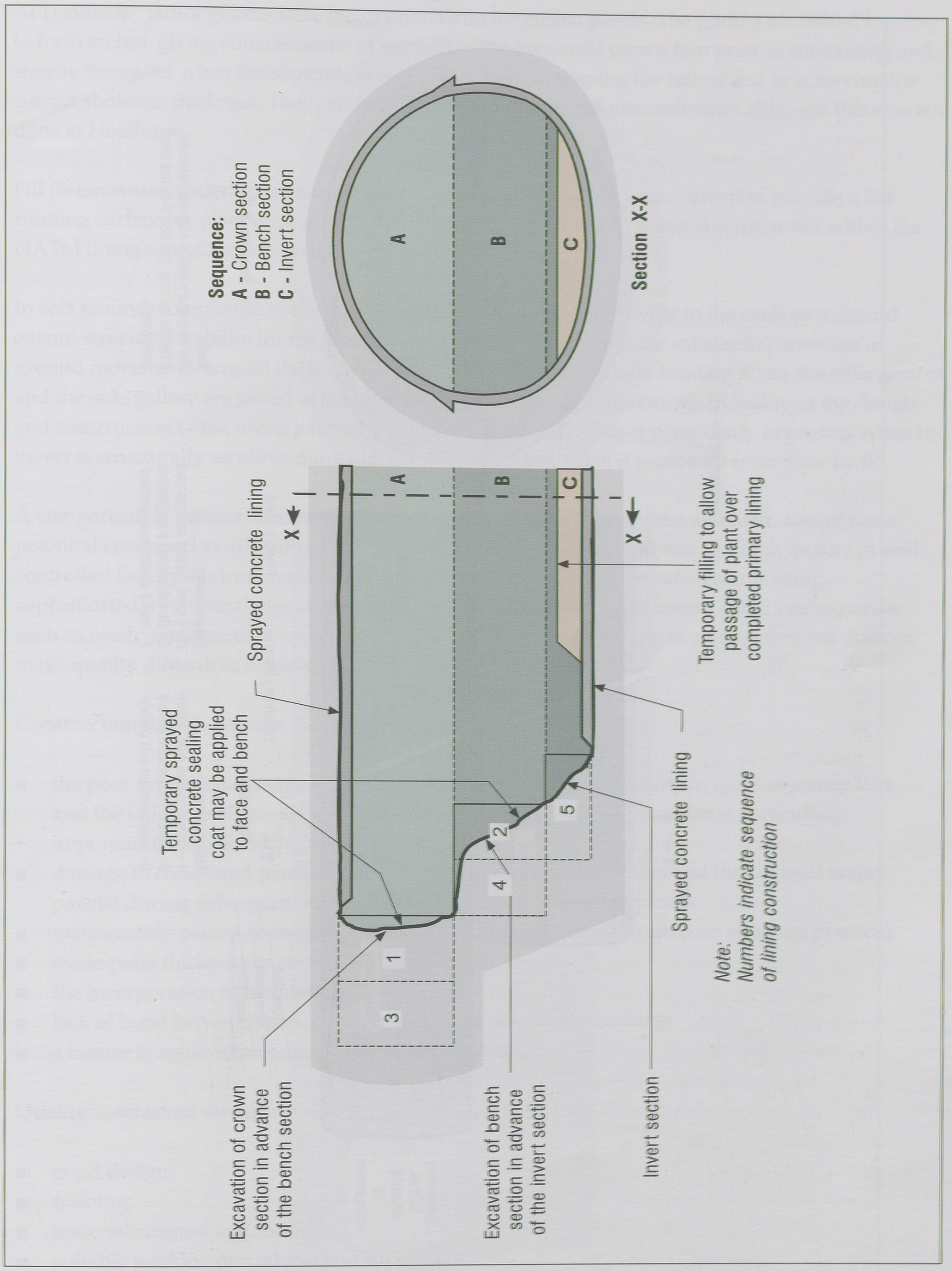


Figure 21 *Example of NATM tunnel excavated in three partial cross-sections*

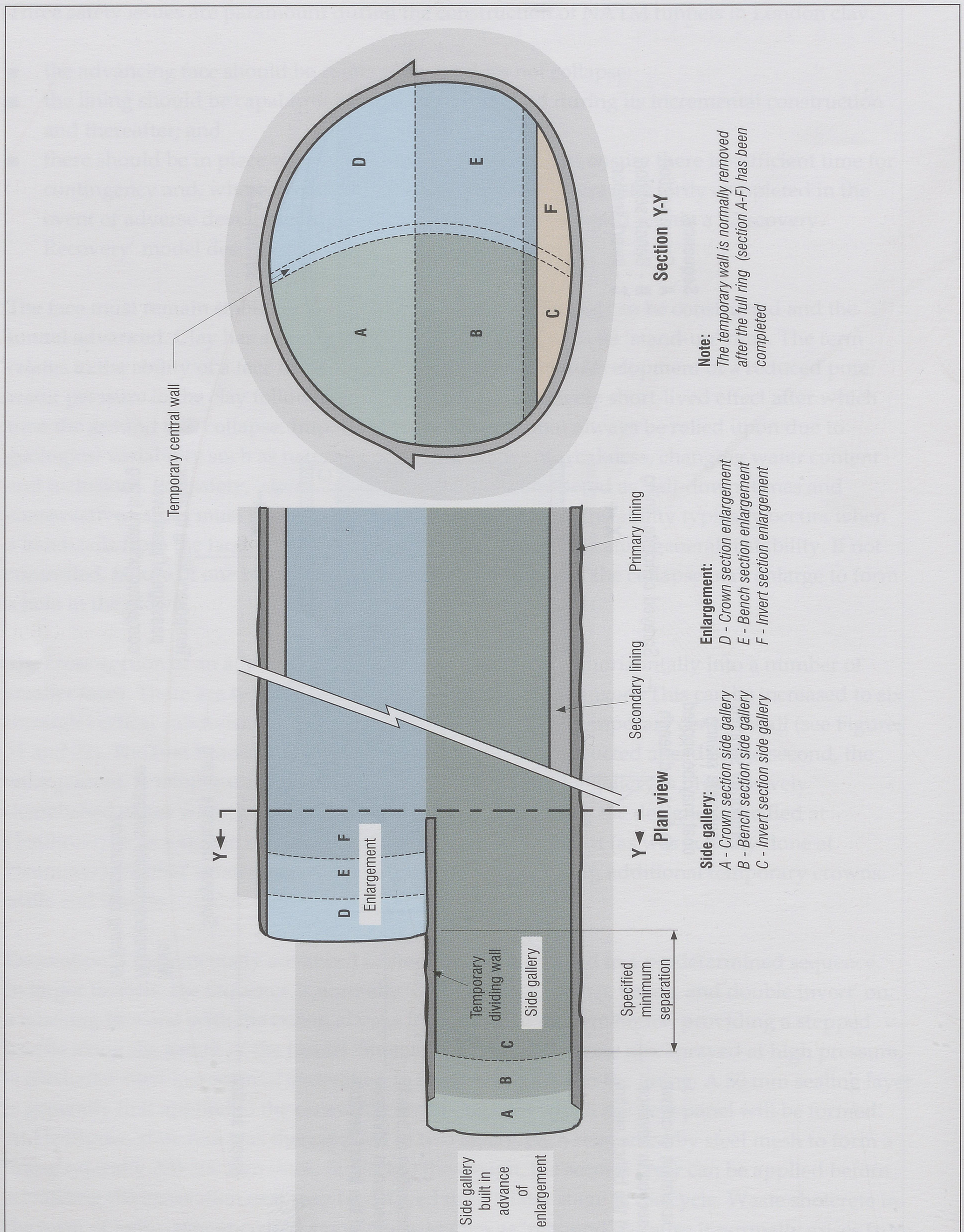


Figure 22 *Example of NATM tunnel excavated in six partial cross-sections*

10 At Heathrow, lattice girders were incorporated into the crown panels. The girders are bolted together to form arches, giving some measure of support to the excavated crown face prior to shotcreting and shortly thereafter when the shotcrete is weak. They help in shaping the tunnel and in achieving the correct shotcrete thickness. They can be provided around the full circumference although this was not done at Heathrow.

11 Fill (ie excavated material) is temporarily placed on the completed tunnel invert to provide a flat running surface for plant during further construction. A permanent lining is constructed within the NATM lining sometime later in the work.

12 In soft ground, completion of the tunnel ring is the most important event in the cycle as it should ensure structural stability for the lining, support for the ground and the substantial cessation of ground movements around the tunnel. This is fully achieved in a twin heading when the enlargement and the side gallery are joined at the invert and the temporary wall removed. Quality in the design and construction of the invert joint secures structural stability. This is particularly important when the invert is structurally sensitive due to a flattened profile and when it is covered from view by fill.

13 A comparison of precast concrete segmental tunnels and NATM provides an illustration of some potential construction difficulties. Precast linings are manufactured off-site to a high quality in well-controlled factory environments and then assembled in the tunnels by small teams using sophisticated mechanical means. NATM linings involve larger on-site teams, using raw materials such as mesh reinforcement, cement, additives and aggregate, working in an environment that can make quality difficult to achieve.

14 Construction defects weaken the lining; these include:

- the poor formation of joints (including the failure to secure continuity in mesh or starter bars and the failure to align adjacent panels through poor joint profiling); this is particularly important in tunnels with flattened invert profiles;
- damage to completed panels (particularly to exposed reinforcement and the edges of invert panels) during subsequent excavation for immediately adjacent panels;
- inadequately placed or compacted shotcrete and voids therein (from poor spraying practice);
- inadequate thickness or strength in the shotcrete;
- the incorporation of rebound material in the lining;
- lack of bond between shotcrete layers leading to low angle cracking;
- a failure to achieve the correct cross-sectional shape.

15 Quality is achieved through:

- good design;
- training;
- materials control and testing;
- suitable working procedures and supervision;
- the specification, installation and use of appropriate monitoring instruments;
- the timely interpretation of monitoring data; and

- an effective quality management system.

16 Monitoring is vital to determine the behaviour of the lining and ground. Unsatisfactory trends must be identified sufficiently early to enable corrective steps to be taken. Careful consideration must be given to the number and location of monitoring points. A number of methods can be used. Direct measurement of movement on a tunnel's cross-section (either to determine absolute movement at set points, convergence along chords, or both) is the most vital and provides the most readily interpretable data. Other monitoring methods include:

- direct measurement by pressure cells of ground pressure on the lining and the development of circumferential stress within it;
- indirectly through extensometers, inclinometers and piezometers within the ground surrounding a tunnel;
- indirectly through surface surveys recording settlement;
- direct observation for signs of movement (ie cracking in the lining).

17 With the exception of piezometers and chord convergence, all were variously employed at the CTA and T4 stations. A layout of the monitoring devices at the CTA station is provided in Figure 23.

18 Direct measurement of movement involves monitoring stations set at regular intervals along a tunnel. At Heathrow, five pins (or targets) were arranged as a star around the cross-section with none in the invert. They were broadly positioned at 10 m intervals. However, the pattern was irregular and, initially, there were only two stations (at ch. 72 and 87) over the 50 m between the stations at ch. 54 and 104. This was unhelpful in monitoring the effects of grouting under Camborne House. More stations were added after the events in August. Where a temporary central wall is used, two of the five pins will be lost as the wall is demolished and two new pins should be placed on the new wall. Chords, that is imaginary straight lines between selected pins, can be directly measured by accurate steel taping. Alternatively, a number of monitoring stations can be surveyed by theodolite from a single position and a computer program then used to determine movement in the pin positions (see Figures 7 and 8 for examples) and, if the program permits, chord movements (see Figure 9). While the distinction between plotting quantified chord changes on the one hand and absolute point movements with subjective interpolation of chord changes on the other may appear small, it is an important one during accurate analysis. Up to the point of compressive failure, changes in chord length are small. However, substantial changes will be detectable if a lining has failed in compression.

19 There were two mostly complete MMSs at CTA by the time of the collapse, one either side of the fuel depot shaft. For practical reasons, MMS II was stepped, with some instruments at ch. 29 and some at ch. 47. Instrumentation at an MMS variously consisted of pressure cells, extensometers and inclinometers.

20 Hydraulic pressure cells were incorporated into the NATM linings at MMSs to measure the loads within the linings and the ground loads acting upon them. Reservations are expressed about the reliability of such cells when used in conjunction with shotcrete. Even when care is taken in the specification, installation and calibration of such instruments, the readings can be unreliable or difficult to interpret, or both.

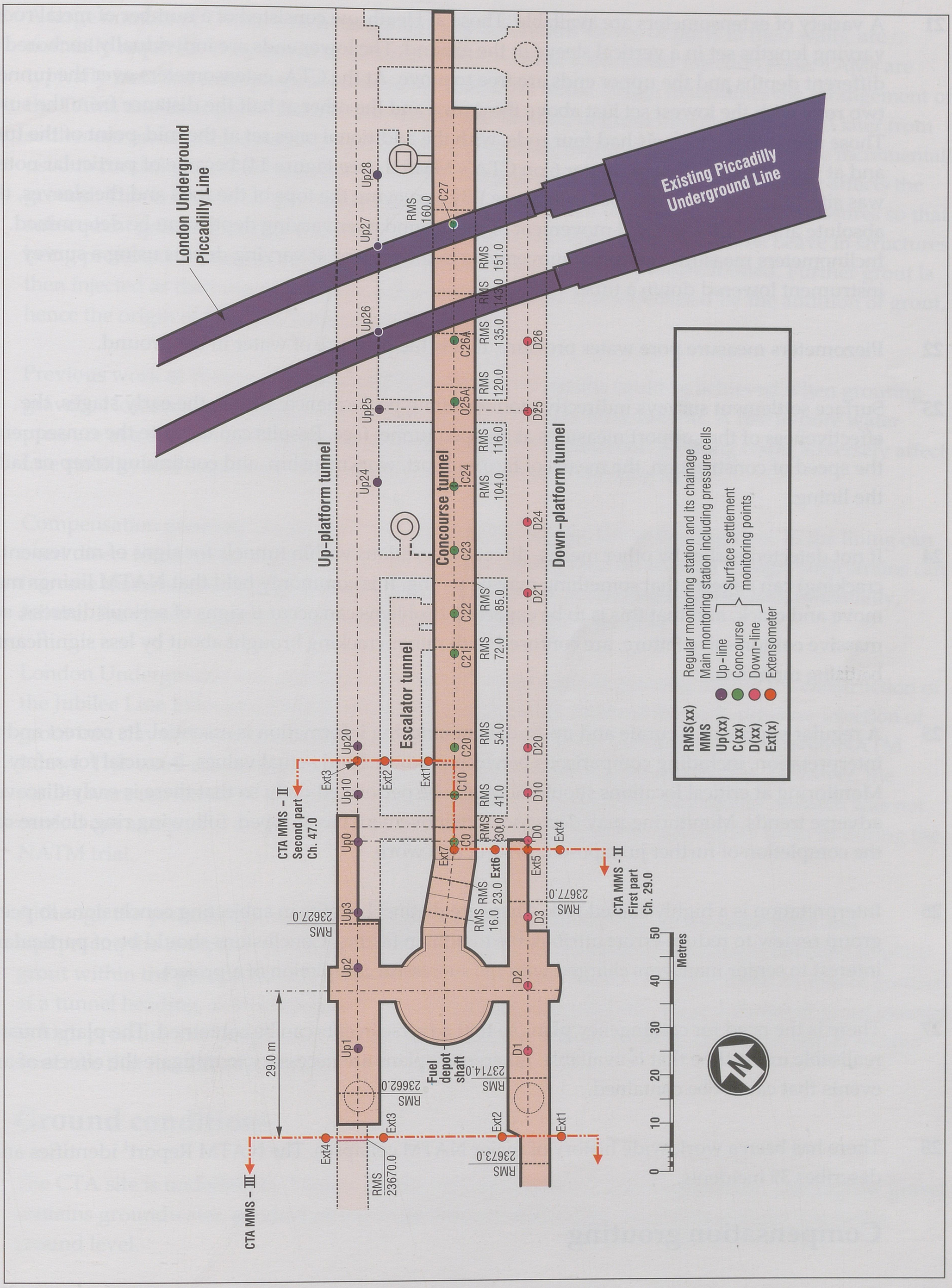


Figure 23 *CTA station layout of monitoring devices*

21 A variety of extensometers are available. Those at Heathrow consisted of a number of metal rods of varying lengths set in a vertical sleeve in the ground. The lower ends are individually anchored at different depths and the upper ends are free to move. At the CTA, extensometers over the tunnels had two rods with the lowest set just above the crown and the other at half the distance from the surface. Those between the tunnels had four rods, with the additional ones set at the mid-point of the tunnels and at their inverts. (Extensometer 6 on CTA's MMS II, (see Figure 14) became of particular note as it was sited close to the centre of the collapse.) By surveying the tops of the rods and the sleeves, the absolute and relative vertical movement of the ground over varying depths can be determined. Inclinometers measure horizontal movements in the ground at varying depths using a survey instrument lowered down a tube.

22 Piezometers measure pore water pressure, that is the pressure of water in the ground.

23 Surface settlement surveys indirectly monitor lining performance, and, in the early stages, the effectiveness of the support measures at an open tunnel face. Results can indicate the consequences of the speed of construction, the means of face support, workmanship, and continuing creep or failure in the lining.

24 If not detected earlier by other means, direct observations within tunnels for signs of movement (ie cracking) can suggest that something may be wrong. It is commonly held that NATM linings may move and crack, and that this is to be expected. Problems can occur if signs of serious distress, such as massive compressive failure, are confused with minor cracking brought about by less significant bending moments.

25 A regular supply of accurate and up-to-date monitoring information is essential. Its correct and timely interpretation, including comparisons between predicted and actual values, is crucial for safety. Monitoring at critical locations should normally be performed daily so that there is early discovery of adverse trends. Monitoring may decrease once movement has stopped, following ring closure or on the completion of further juxtaposed construction work.

26 Interpretation is a highly skilled task. There are distinct benefits in subjecting conclusions to peer group review to reduce errors attributable to human factors. Conclusions should be of particular interest to senior managers charged with the successful completion of a project.

27 There is the need for contingency plans so that adverse events can be contained. The plans must be realisable in the time that is available. Emergency plans are necessary to mitigate the effects of any events that cannot be contained.

28 There has been a worldwide history of major NATM collapses. The NATM Report[1] identifies and describes 39 incidents.

Compensation grouting

29 Compensation grouting is a process where grout is injected into the ground above a tunnel and below buildings, etc, through long pipes (with internal packers), known as tubes-à-manchettes or TAMs.

A large number of TAMs, which have a series of non-return valves or ports in their walls, are normally required. They can be at different levels to create a thickened injection zone. TAMs are typically installed from purpose-constructed shafts. An initial design determines the arrangement of the TAMs and their ports. The amount, timing and location of grout injection is decided later from settlement monitoring data and experience. In most cases, multiple grouting phases are incrementally used to control ground settlement as it occurs. Some grout is injected before tunnelling affects the ground. This is known as 'preconditioning'. It is said to stiffen the ground by closing fissures so that subsequent grouting can have immediate beneficial effect. The detection of some heave in structures being protected is taken as an indication that the ground has been preconditioned. Further grout is then injected as the tunnel is constructed so that settlement is compensated by the addition of grout, hence the origin of the term 'compensation grouting'.

30 Previous work at Waterloo Station had shown that good results could be achieved when grouting gravels. However, potentially adverse affects in London clay were unclear. A rise in pore water pressure at a tunnel face brought about by juxtaposed compensation grouting could adversely affect face stability and require grouting 'exclusion zones' close to working faces.

31 Compensation grouting can deform completed tunnel linings. Grout flowing close to the lining can exert direct forces on it. More likely, vertical strains are imposed on affected linings. Such strains can increase distortions in linings and may adversely affect them, causing cracking and, potentially, failure. The closer a grouting layer to a tunnel, the more likely the effect.

32 London Underground was considering the use of compensation grouting during the construction of the Jubilee Line Extension Project. A trial at London Bridge involved the high-pressure injection of grout into clay and was later extended to include compensation grouting above a driven NATM tunnel. This work was in hand at the time Heathrow Express began construction. However, the results were too late to be of benefit to Balfour Beatty. It is regrettable that similar research was not carried out as a part of the Heathrow Express Project. There was the opportunity to do so during the NATM trial.

33 Although the processes of compensation grouting and grout jacking use the same plant and equipment, the two processes should be differentiated. Compensation grouting is intended to place grout within the ground mass to compensate for surface settlement, brought about by loss of ground at a tunnel heading, as it occurs; whereas grout jacking uses relatively large volumes of grout injected at high pressure into the ground, and, as a consequence, putting considerable forces into it, to lift a structure that has already settled.

Ground conditions

34 The CTA site is underlain by Taplow gravel, beneath which is found London clay. The Taplow gravel contains groundwater, perched on top of the less permeable clay, at a depth of about 3 m below ground level.

35 London clay is a geological name given to materials laid down between about 51 million and 57 million years before the present. The material varies across the UK, but in this area, and at the depths

of the tunnels, consists of a hard grey and relatively impermeable clay. The clay mass is crossed by planes of weakness, termed 'fissures', 'joints' or 'discontinuities'.

36 Clays are complex materials. Mineral particles derived from older rocks form minute flaky crystals with layer-lattice structures. Water is present in thin films around these particles and it fills the pore spaces between them. The strength and stiffness of the clay decreases as the water content is increased. The minute pore spaces make clays highly impermeable to the movement of water.

37 In many ways London clay is an excellent tunnelling medium. Its low permeability means that water will not flow rapidly into the tunnel during construction. Its modest strength means that it is relatively easy to excavate. The ability, or otherwise, of an excavated face to stand unsupported for sufficient time to allow construction of short sections of the lining is a key issue (see paragraph 7 of this appendix).

38 Before tunnel construction, the clay will be under vertical and horizontal pressures resulting from the weight of the ground that is overlaying, or has previously overlaid, it. Excavation reduces these pressures, and the clay will then move towards the excavated space, partly by the opening of fissures, by sliding along them, and in the longer term by sucking in water into the clay itself. The presence of discontinuities may give rise to localised failures in the tunnel face (see paragraph 7 of this appendix) and the action of tunnelling may cause the surrounding clay to become softer, as a result of sucking in water, or to weaken, as a result of opening of fissures or breaking down of the clay blocks between them. This can lead to more widespread failure where support is insufficient, either in the heading or around an inadequate lining.

APPENDIX 2: Construction progress chart

1 A programme illustrating the work carried out during construction of the CTA tunnels up to the time of collapse is shown at Figure 24. The programme was prepared post collapse using site records and indicates the sequence of activities by time and location. The top and bottom horizontal axes variously show time. The right-hand vertical axis shows chainages along the concourse tunnel, that is the distance in metres to points in the tunnel when measured from the middle of the fuel depot shaft. A longitudinal section of the concourse tunnel is shown on the left-hand side. The 19 m diameter fuel depot shaft occupies the chart from about ch. -10 to +10, Camborne House at about ch. 57 to 72 and the two Piccadilly Line tunnels at about ch. 140 and 160.

2 Progress in constructing the side galleries and enlargements of the concourse tunnel and the two platform tunnels is shown by the sloping red and green lines. The long green line indicates when excavation started for the concourse tunnel side gallery at points along the tunnel. It can be seen that excavation started at the fuel depot shaft in week 1 and reached ch. 200 by week 22. Likewise, the long red dotted line shows shotcreting of the enlargement invert, the last operation in constructing the concourse tunnel. This was first achieved by about day 23 and had reached ch. 180, just beyond the north escape shaft, by week 22.

3 Construction of the up-line and down-line platform tunnels 'north'[13] is shown by the two pairs of red and green lines respectively, starting around days 120 and 140. The construction of these two platform tunnels in the opposing direction is shown by the green and red lines between days 50 and 135.

4 The straight steeply sloping red dotted line shows the planned rate for constructing the tunnels at 3.2 m/day. The actual rate was only 1.3-1.7 m/day. Thus, the planned time to reach the south escape shaft was about 30 days but it actually took 70 days.

5 Other events are shown by black vertical lines, boxes or dots. Hence, the discovery on day 52 of a horizontal crack in the temporary central wall at about ch. 48-60 is shown by a vertical black line extending from ch. 48-60 at day 52. The installation of the TAMs in preparation for compensation grouting at Camborne House is shown by the rectangle under Camborne House at days 67-70 and compensation grouting is shown by the three rectangles under Camborne House at days 74-82, 84-88 and 121-123. Repairs to the concourse tunnel invert up to about ch. 40 between days 149-151 are shown by the rectangle near the bottom right-hand corner of the chart. Events occurring on a single day and at a single point are shown by black dots.

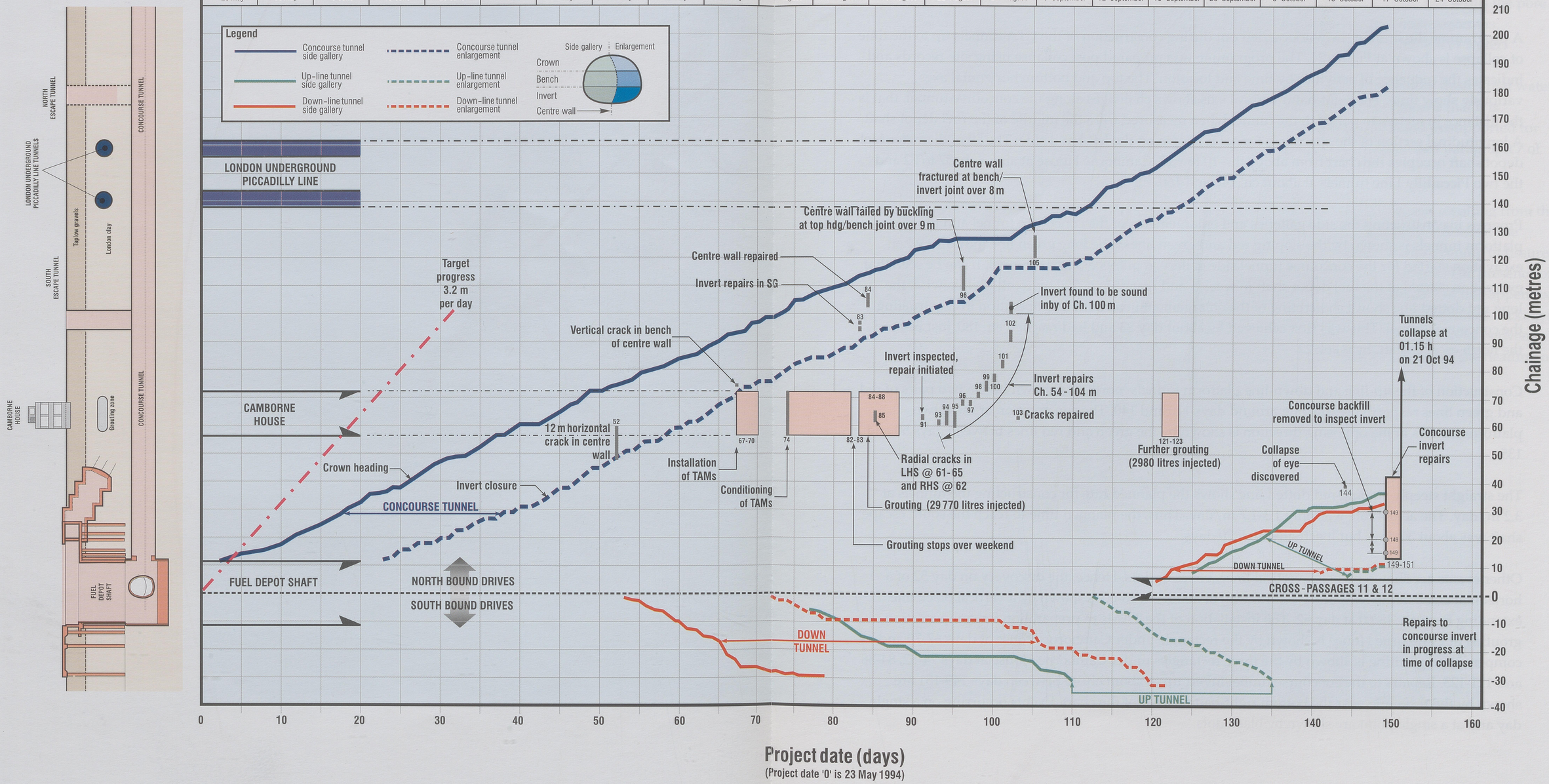

MAY 94
JUNE 94
JULY 94
AUGUST 94
SEPTEMBER 94
OCTOBER 94
Wk 1 Week starting 23 May
Wk 2 Week starting 30 May
Wk 3 Week starting 6 June
Wk 4 Week starting 13 June
Wk 5 Week starting 20 June
Wk 6 Week starting 27 June
Wk 7 Week starting 4 July
Wk 8 Week starting 11 July
Wk 9 Week starting 18 July
Wk 10 Week starting 25 July
Wk 11 Week starting 1 August
Wk 12 Week starting 8 August
Wk 13 Week starting 15 August
Wk 14 Week starting 22 August
Wk 15 Week starting 29 August
Wk 16 Week starting 5 September
Wk 17 Week starting 12 September
Wk 18 Week starting 19 September
Wk 19 Week starting 26 September
Wk 20 Week starting 3 October
Wk 21 Week starting 10 October
Wk 22 Week starting 17 October
Wk 23 Week starting 24 October
Legend
Concourse tunnel side gallery
Up-line tunnel side gallery
Down-line tunnel side gallery
Concourse tunnel enlargement
Up-line tunnel enlargement
Down-line tunnel enlargement
Side gallery
Enlargement
Crown
Bench
Invert
Centre wall
LONDON UNDERGROUND PICCADILLY LINE
Target progress 3.2 m per day
Centre wall repaired
Invert repairs in SG
Centre wall fractured at bench/invert joint over 8 m
Centre wall failed by buckling at top hdg/bench joint over 9 m
Invert found to be sound inby of Ch. 100 m
Vertical crack in bench of centre wall
Invert inspected, repair initiated
Invert repairs Ch. 54 - 104 m
Cracks repaired
CAMBORNE HOUSE
12 m horizontal crack in centre wall
Crown heading
Invert closure
CONCOURSE TUNNEL
Installation of TAMs
Conditioning of TAMs
Radial cracks in LHS @ 61-65 and RHS @ 62
Grouting (29 770 litres injected)
Grouting stops over weekend
Further grouting (2980 litres injected)
Collapse of eye discovered
Concourse backfill removed to inspect invert
Concourse invert repairs
Tunnels collapse at 01.15 h on 21 Oct 94
FUEL DEPOT SHAFT
NORTH BOUND DRIVES
SOUTH BOUND DRIVES
DOWN TUNNEL
UP TUNNEL
CROSS-PASSAGES 11 & 12
Repairs to concourse invert in progress at time of collapse
Chainage (metres)
Project date (days)
(Project date '0' is 23 May 1994)
NORTH ESCAPE TUNNEL
SOUTH ESCAPE TUNNEL
LONDON UNDERGROUND PICCADILLY LINE TUNNELS
Taplow gravels
London clay
Grouting zone

Figure 24 *Tunnelling activities at the CTA*

APPENDIX 3: Summary of major cracking problems at the station complexes recorded by Geoconsult during the works

Dates (1994)	*Location*	*Remarks*
14 July	T4 NVT*	Damage to side wall due to collision by excavator
14 July	CTA concourse tunnel central wall	Horizontal crack at invert to bench joint, ch. 47.9-59.4
17 July	T4 NVT	4 m crack in side gallery crown. Opened to 2-3 mm and remained stable
13 August	CTA down-line platform S - central wall	Two vertical cracks and shotcrete coming free at base after work had stopped for several days
13 August	CTA - junction of cross-passage from fuel depot shaft to up-line platform	Crack at intersection of cross-passage and centre wall of the up-line platform before enlargement started. Repaired, reopened and then remained stable
16 August	CTA concourse tunnel	Radial cracks at ch. 61 and 65 in side walls and rising from below temporary fill. Continued to propagate. Investigation later carried out and failed invert found. Extensive repairs continued, mostly towards the face, until 2 September
27 August	CTA concourse tunnel central wall	Horizontal cracks at crown and bench joint, ch. 108.3-117.0, due to poor shape, insufficient shotcrete and lack of mesh overlap
31 August	CTA down-line platform tunnel central wall	Cracking due to poor shape
1 September	CTA down-line running tunnel	Invert damaged by excavator. Repair revealed a lack of mesh overlap between bench and invert, that shotcrete was delaminating and in places was insufficiently thick
5 September	CTA concourse tunnel central wall	Horizontal cracks at crown to bench joint, ch. 120-128, due to poor shape
13 September	T4 junction of NVT enlargement and up-line platform	Crack 2 m long x 2 mm wide. Stable and not propagating
24 September	CTA junctions of cross-passages from fuel depot shaft to up-line and down-line platforms	Horizontal cracks in the eyes of both cross-passages at both enlargements which had yet to commence
9 October	T4 south lower concourse enlargement	3-4 m horizontal cracks to both side walls. 20-30 mm gaps behind delaminating shotcrete of insufficient thickness
19 October	CTA tunnels	Cracking to walls and invert of concourse tunnel, later developing into the major collapse on 20/21 October
30 October	T4 NVT	Cracking along centre of invert when fill removed for remedial work due to poor workmanship

* NVT = north ventilation tunnel at T4

APPENDIX 4: Summary of the probable collapse mechanism

1 Repetitive construction defects occurring in the CTA concourse tunnel made it unsound from the outset. This is clear from monitoring data available at the time (eg Figures 7 and 8). The upper display in Figure 8 shows that the vertical plots of all targets continued to fall with no sign of slowing. Likewise, the lower display of horizontal movement shows that 0035 and 0038, the lower targets on the left- and right-hand walls, were moving inwards with no signs of stopping. Movements were due to the ground forces acting on the lining with its defective invert.

2 Grout jacking began on 5 August 1994 with early results showing a reversal in settlement trends of Camborne House. However, tunnel monitors indicated that there was an immediate detrimental response with significant increases in both vertical and lateral movements at ch. 30, 41, 54 and 72 (Figures 10 and 12). These suggested that forces due to grout jacking were causing excessive lining movements.

3 There was ample evidence of a major problem, in particular poor workmanship, from results of in-tunnel monitoring and from the mode of invert joint failure discovered during repairs. Taken together, it indicated that the invert was damaged, most probably between ch. 23 and ch. 104, due to built-in defects or to grout jacking or to a combination of both (see Figures 25 and 26).

4 From the limited data collected in the month before the collapse, it is clear from increased surface settlement readings, extensometer readings of large ground strains, and, in particular, the increasing chord strains, that the lining between ch. 30 and 54 was failing to adequately support the ground. Commencing the two adjacent platform tunnel drives accelerated movement trends as drives approached the various monitoring stations.

5 In addition to the trough which was expected to develop along the line of the tunnel as it was excavated, a shallow crater, centred around ch. 30, had formed over the 30 days preceding the collapse (Figure 13). It was indirect evidence of movement in the tunnel lining around this point.

6 Direct evidence was provided by in-tunnel monitoring data. A summary of the data for ch. 30 is provided by Figure 27. Over the 13 days before the collapse, key performance indicators were showing that movements in and around the concourse tunnel lining at ch. 30 and 41 were accelerating. In particular, the chord strains (the percentage change in original chord length) across the lower half of the concourse tunnel lining were demonstrating that the lining was not behaving as intended and that failure had taken place in the invert with the result that the lining was providing little support to the ground. These readings contrasted unfavourably with those at ch. 87 of the concourse tunnel which indicated that movement ceased when a sound invert was formed (Figure 9).

7 The extent of strain across the defective invert would have been associated with the transference of load to the adjacent clay and its progressive weakening as a result of dilation caused by shear strain. The vertical strains measured by extensometer 6 (Figure 14) are almost certainly associated with shear

strains of the clay across this extensometer as the invert closure was accompanied by strains within the clay. Although defective, it is likely that the tunnel invert, coupled with the loading and strutting effects of the temporary clay fill upon it, added to the capability of the clay beneath the invert to transmit in the short term the horizontal loads caused by the presence of the concourse tunnel (see Figure 28).

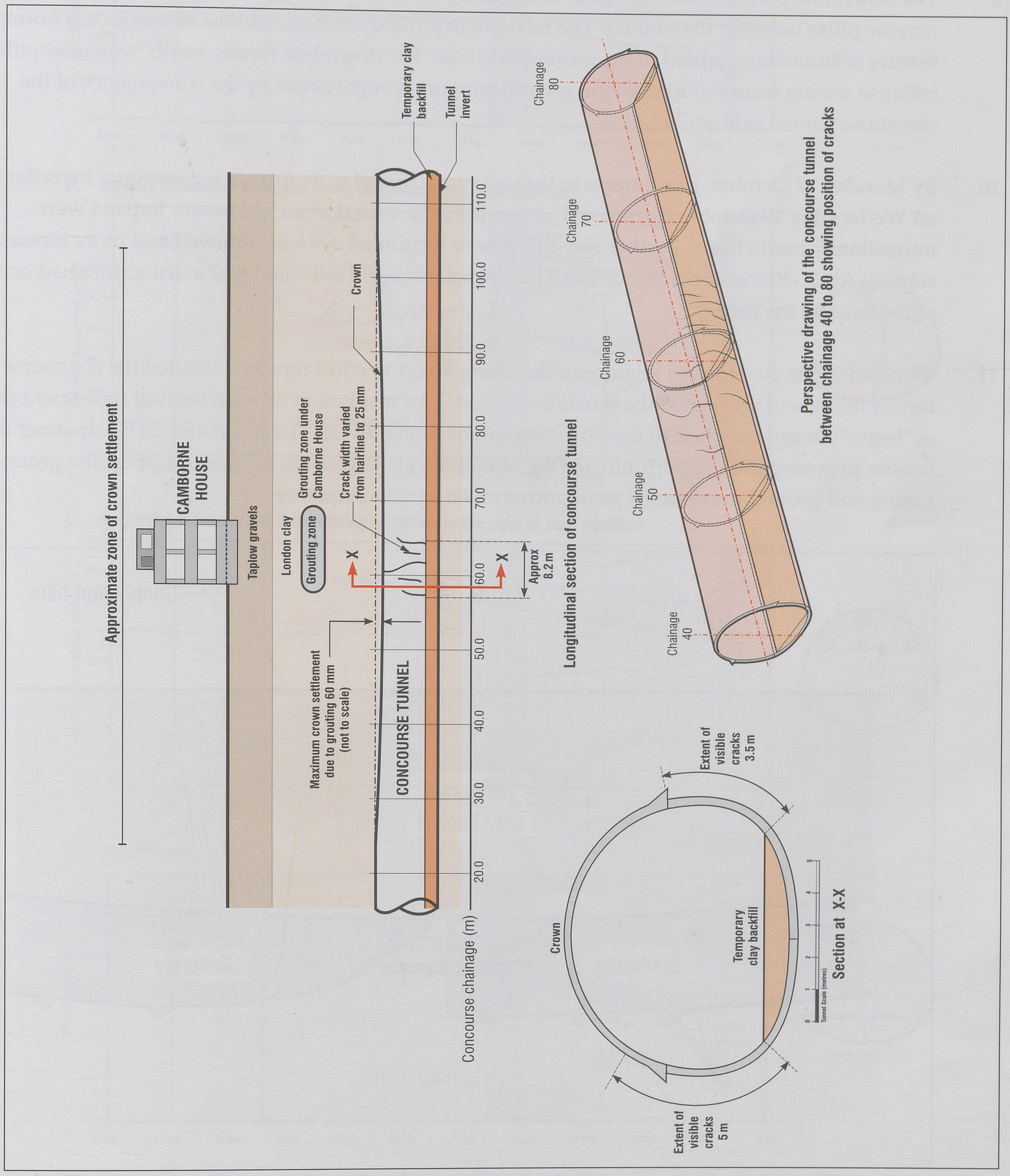


Figure 25 *Cracks above clay backfill of the concourse tunnel - August 1994*

8 The trends of accelerating movement in the concourse tunnel lining began when the platform tunnel 'north' drives commenced. The movements were initially dismissed as an expected result of driving the new headings, although the concourse tunnel was affected for a length well beyond the zone of influence of the platform tunnels.

9 The down-line platform tunnel 'north' side gallery was driven into the sheared clay, reducing it to a narrow pillar between the tunnels. The increase in ground loads around the tunnel face, a normal feature of tunnelling, added to the ground loadings. The down-line tunnel 'north' was susceptible to collapse arising from reduced lateral ground support brought about by the convergence of the concourse tunnel side walls.

10 By Monday 17 October, movements in the concourse tunnel were further accelerating. Investigations on Wednesday 19 October by removal of the clay fill revealed a cracked invert. Repairs were immediately put in hand. Further clay fill close to the tunnel eye was removed and more repairs started. At ch. 30 a major circumferential crack below the fill indicated that a dislocation had occurred at the bend in the tunnel.

11 Removal of the clay fill and sections of the lining invert to effect repairs unloaded the concourse tunnel lining and weakened the remaining invert. This resulted in upward vertical movement (known as 'heave') in ground close to the invert and in the lining invert. The speed and ad hoc manner of the repairs provided little opportunity for the new shotcrete to gain strength and support the ground. Lining and ground movements were uncontrolled as a consequence.

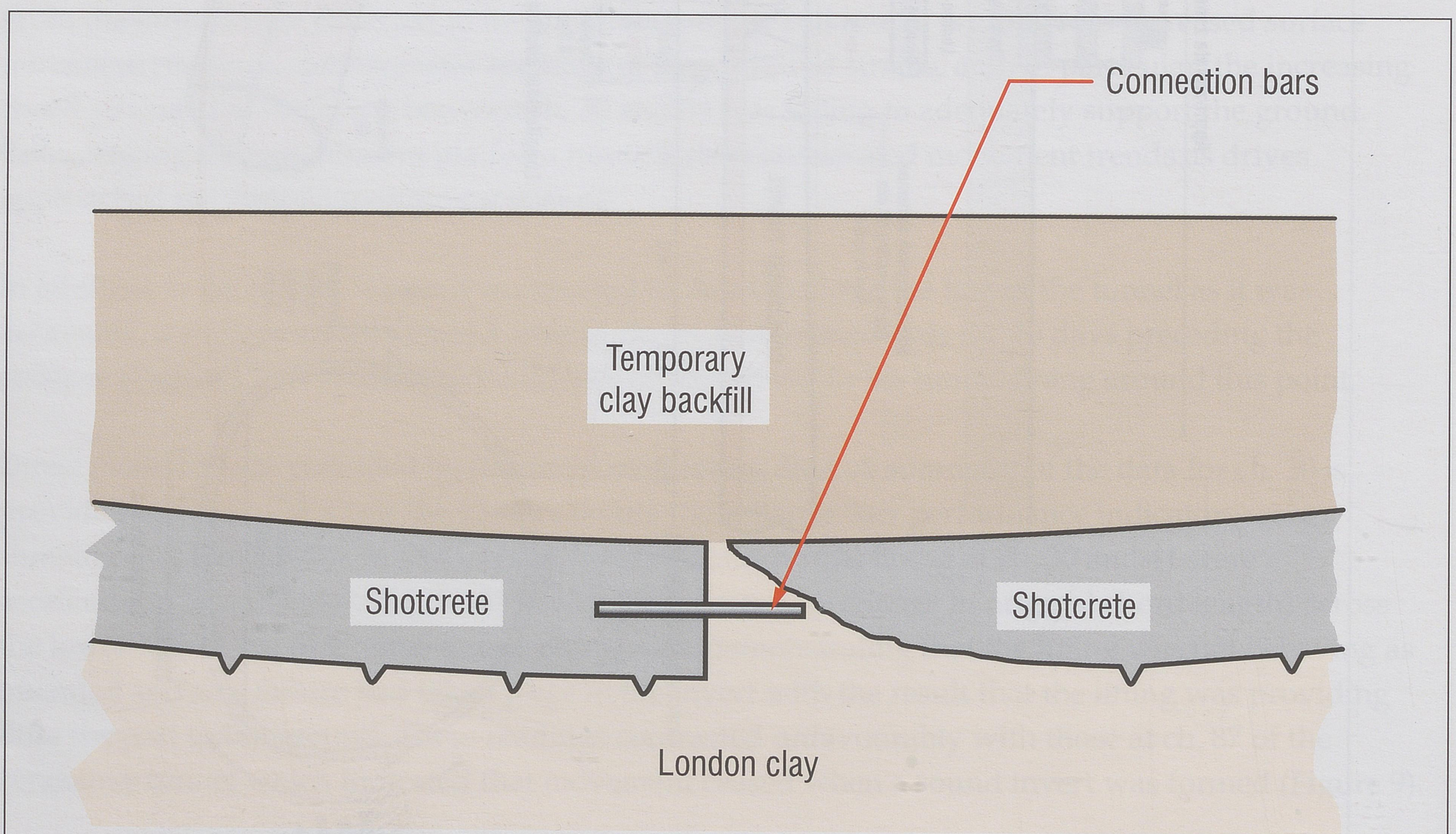


Figure 26 *Condition of invert joint observed during repairs at ch 72-74 m*

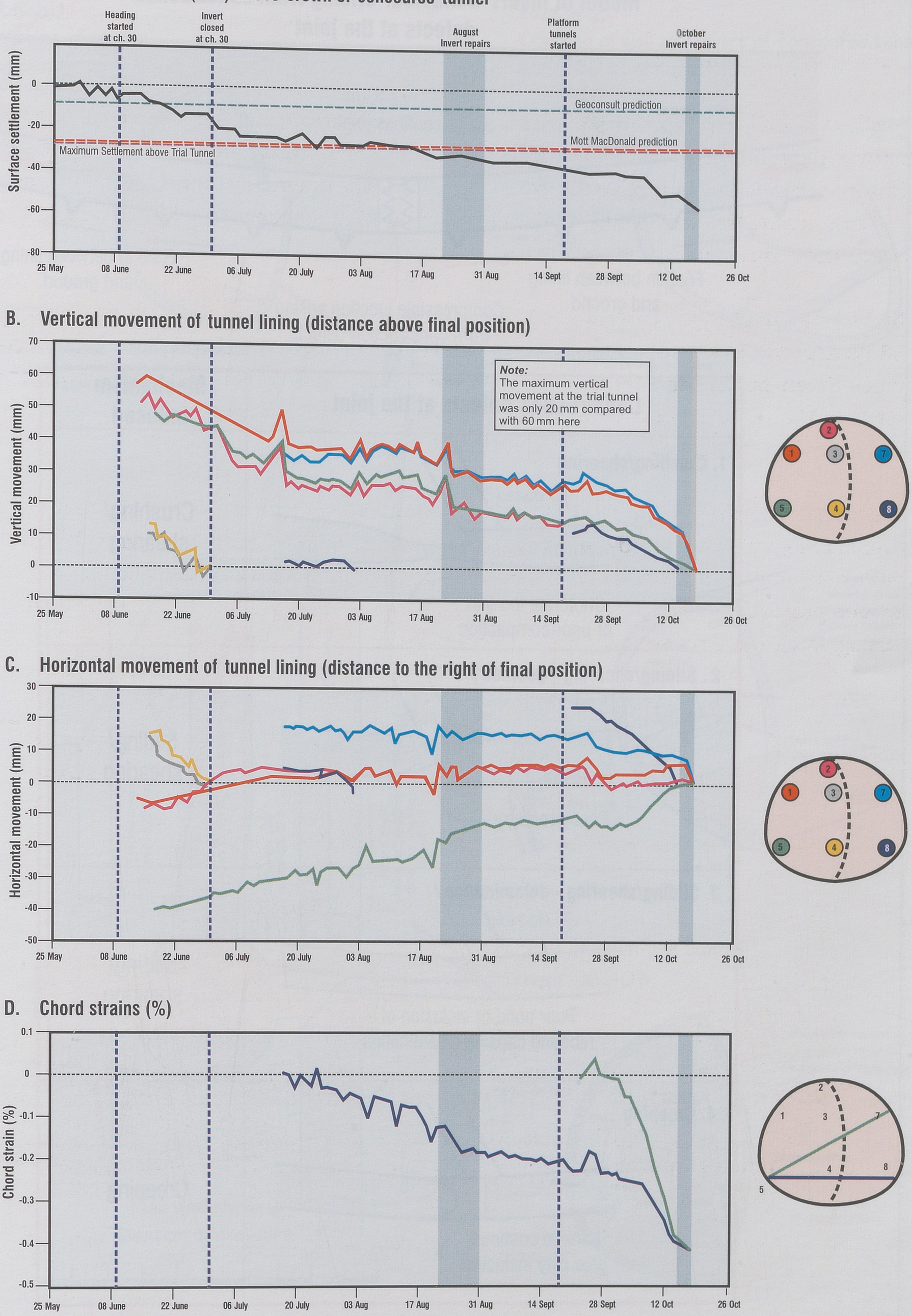
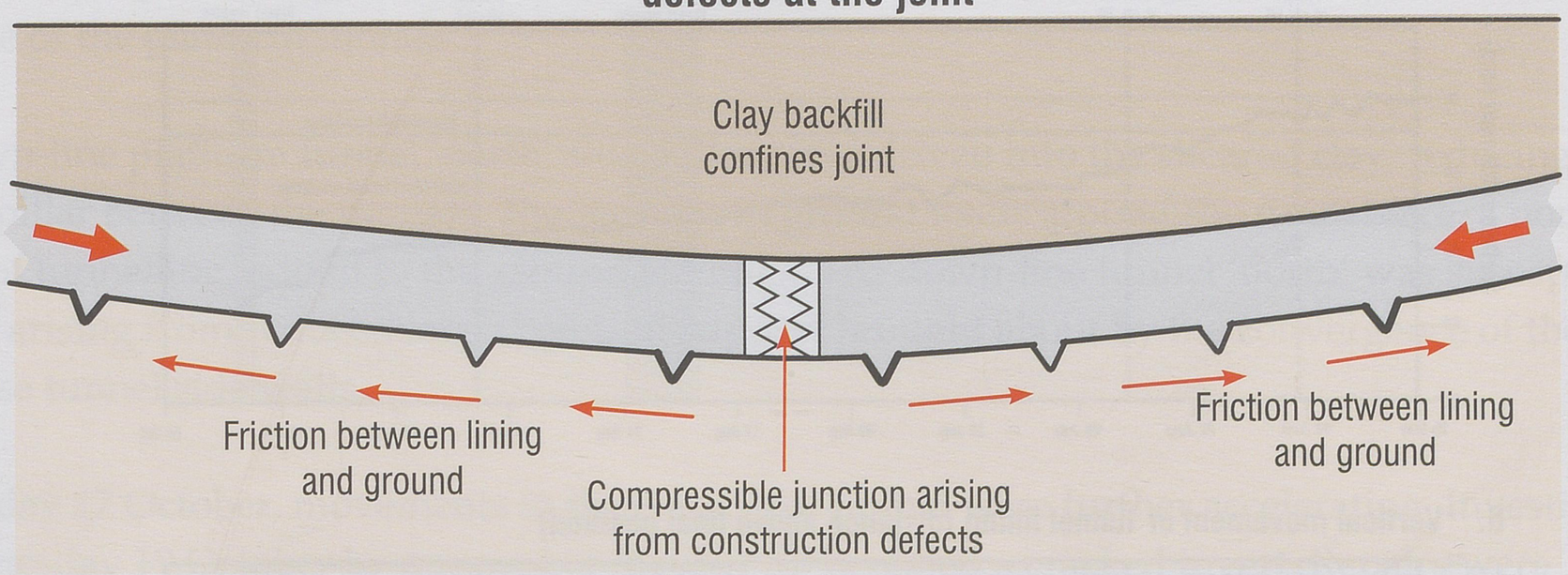


Figure 27 *Summary of monitoring data at concourse tunnel, ch 30*

Model of invert behaviour arising from construction defects at the joint


Clay backfill
confines joint
Friction between lining and ground
Compressible junction arising from construction defects
Friction between lining and ground

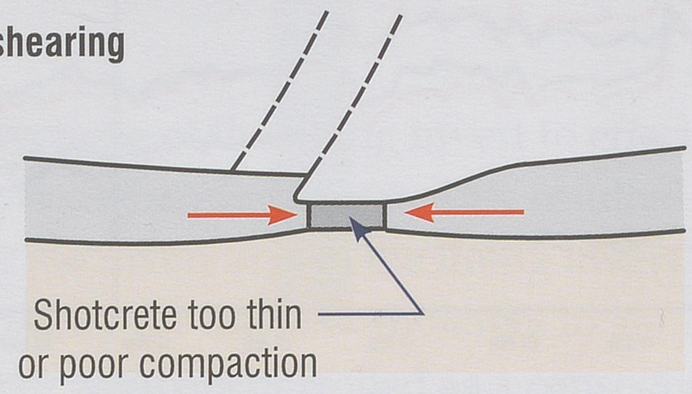
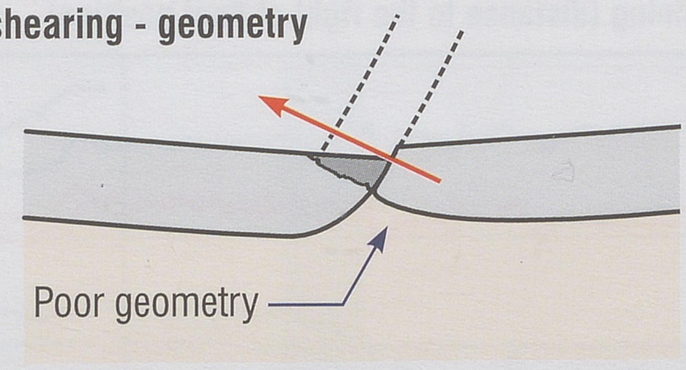
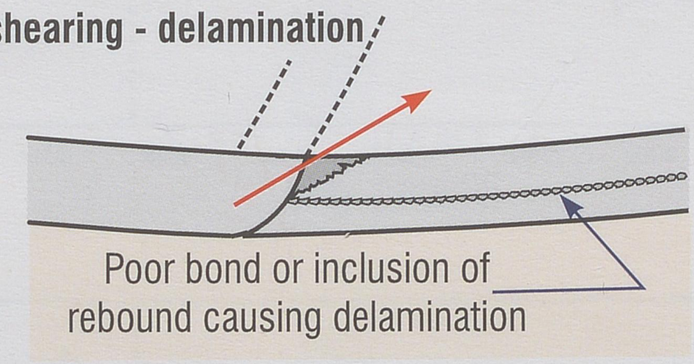
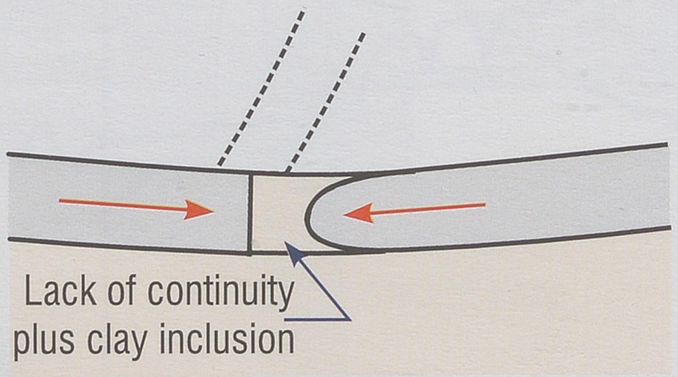
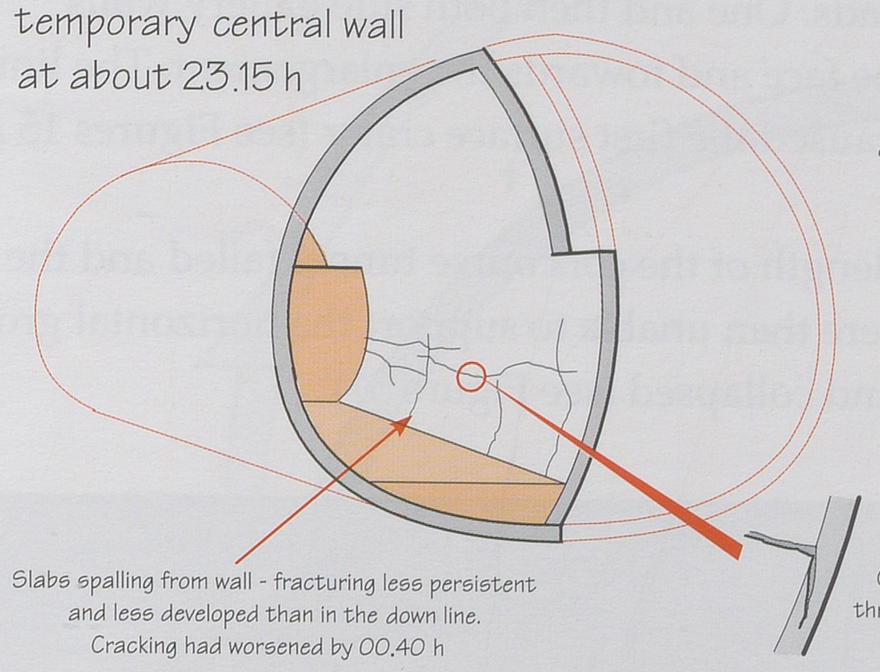
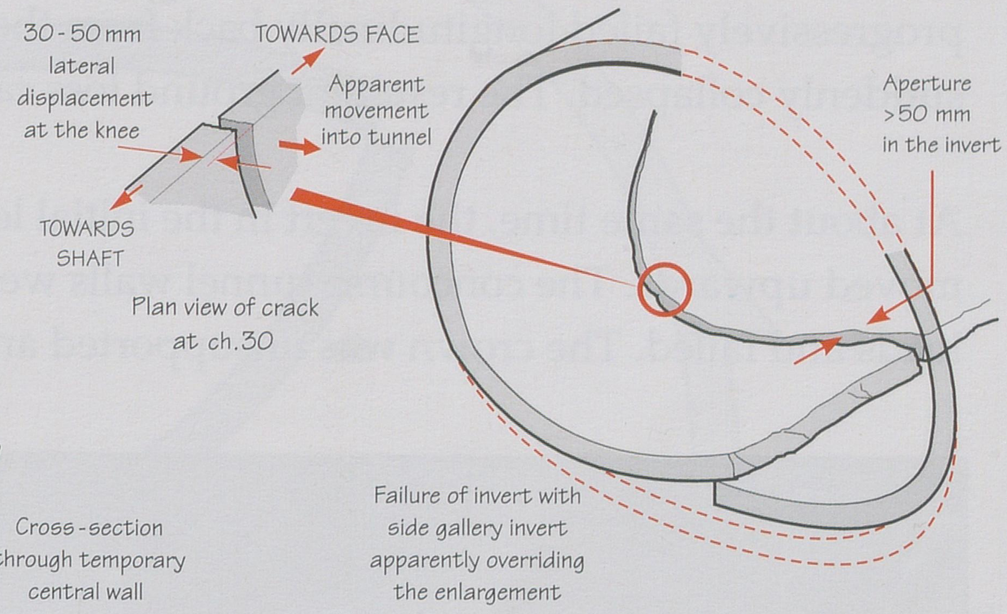
Construction defects at the joint	Mechanism induced
1. Crushing/shearing 	Crushing/ shearing
2. Sliding/shearing - geometry 	Sliding/ shearing
3. Sliding/shearing - delamination 	Sliding/ shearing
4. Creeping 	Creeping

Figure 28 *Generic model of invert joint behaviour and contributory construction defects*

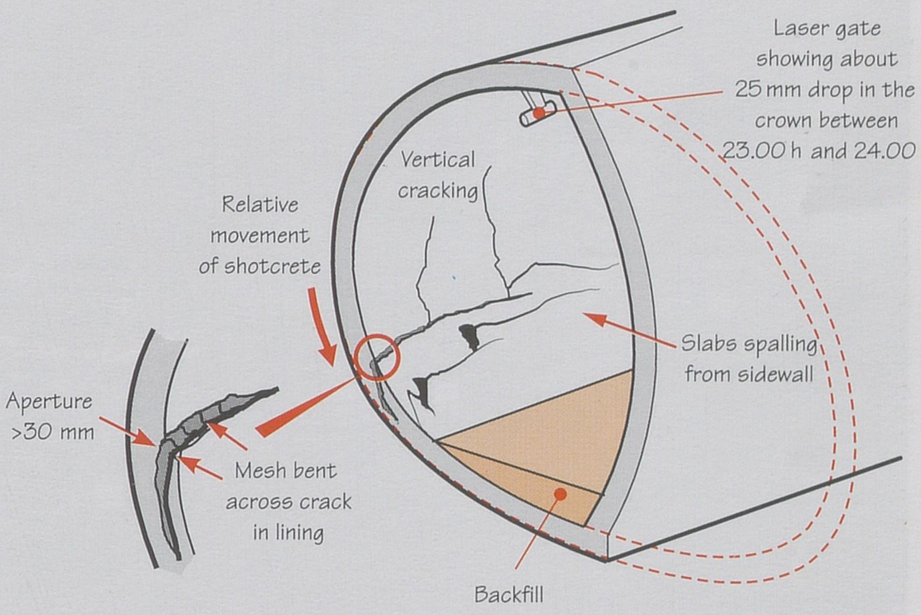
Sketch ①
Cracking of up-line temporary central wall at about 23.15 h


Slabs spalling from wall - fracturing less persistent and less developed than in the down line. Cracking had worsened by 00.40 h
Cross-section through temporary central wall

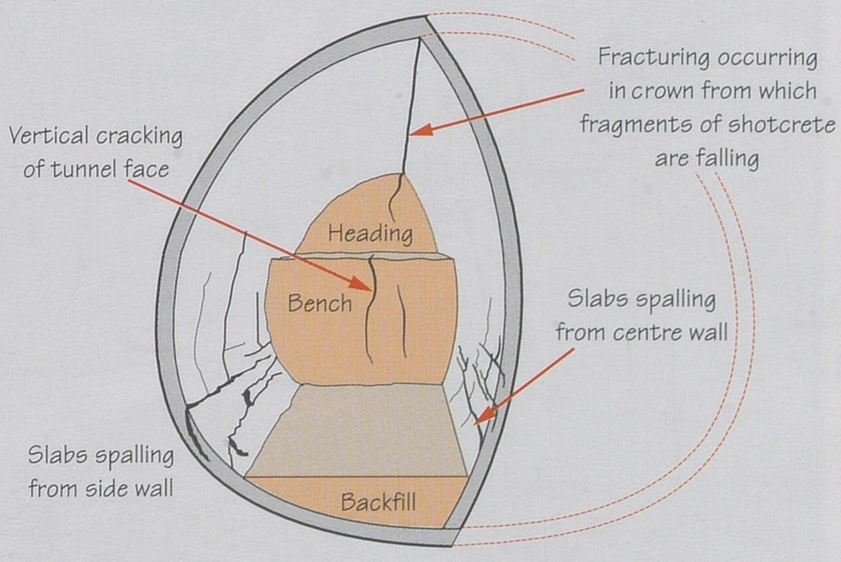
Sketch ②
Cracking of wall and invert of concourse tunnel at ch. 30 at about 23.15 h


30 - 50 mm lateral displacement at the knee
TOWARDS FACE
Apparent movement into tunnel
TOWARDS SHAFT
Plan view of crack at ch.30
Aperture >50 mm in the invert
Failure of invert with side gallery invert apparently overriding the enlargement

Sketch ③
Cracking of down-line tunnel at about 23.15 h


Laser gate showing about 25 mm drop in the crown between 23.00 h and 24.00 h
Vertical cracking
Relative movement of shotcrete
Slabs spalling from sidewall
Aperture >30 mm
Mesh bent across crack in lining
Backfill

Sketch ④
Cracking of down-line tunnel at about 00.40 h


Fracturing occurring in crown from which fragments of shotcrete are falling
Vertical cracking of tunnel face
Heading
Bench
Slabs spalling from centre wall
Slabs spalling from side wall
Backfill

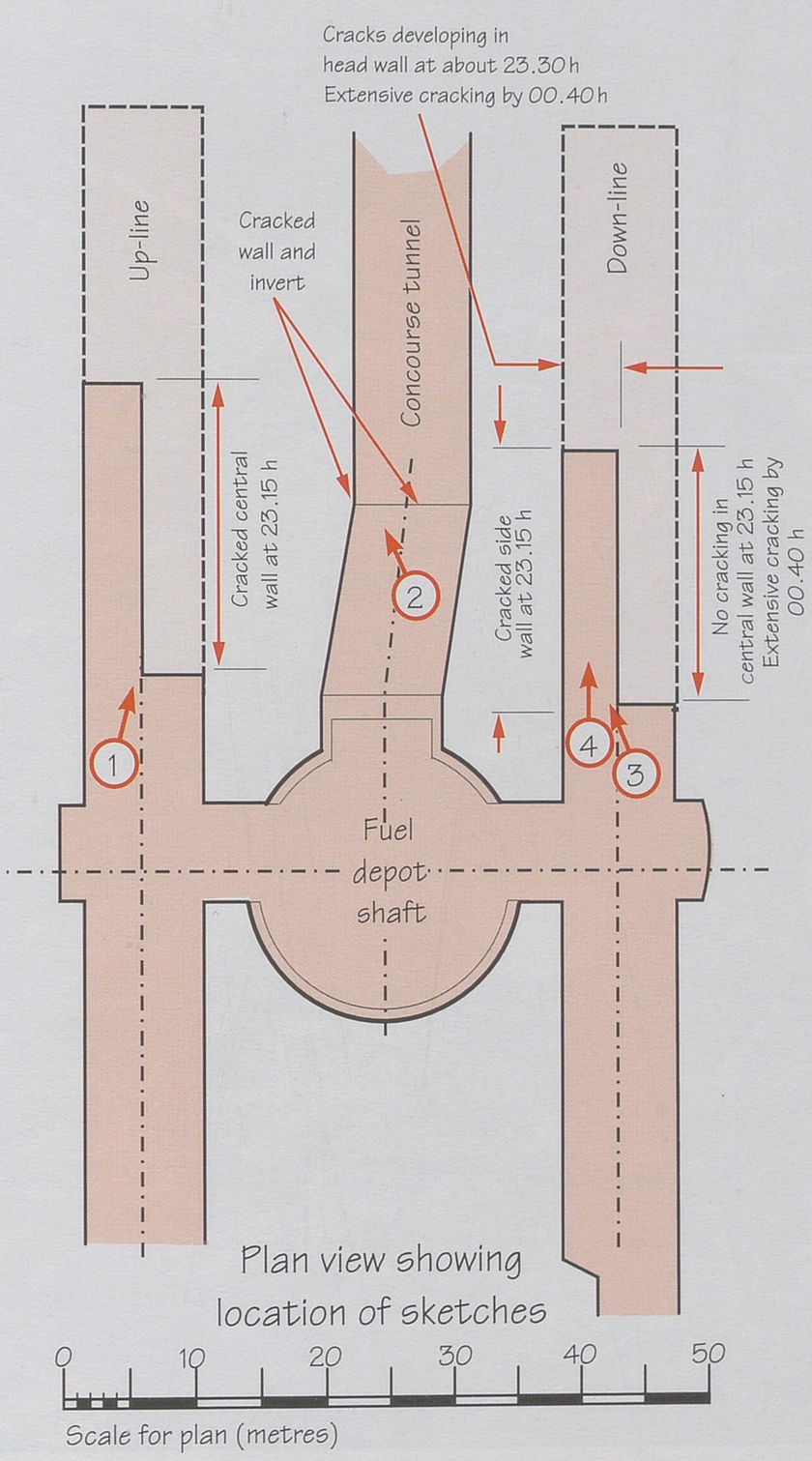


Figure 29 *Sketches of cracking observed by the 'NATM engineer' at about 23.15 h and 00.40 h*

12 The weakened clay at the unsupported face of the down-line platform tunnel 'north' began to collapse, initially by spalling at the bench. The weakened clay pillar between this tunnel and the concourse tunnel failed to provide the necessary ground support to the down-line side gallery. It was in turn unable to carry the additional ground loads. One and then both side gallery walls progressively failed longitudinally back from the face and towards the enlargement. The lining suddenly collapsed. The resultant ground loss caused the first surface crater (see Figures 15 and 18).

13 At about the same time, the invert in the initial length of the concourse tunnel failed and the invert moved upwards. The concourse tunnel walls were then unable to support the horizontal ground loads and failed. The crown was unsupported and collapsed (see Figure 31).

Figure 30 *Down-line platform tunnel 'north' post collapse. The photograph shows a part of the lining at about ch. 18.5 and viewed looking towards the fuel depot shaft from the tunnel face. The lining was exposed during subsequent excavation at the site (Reproduced with the permission of BAA)*

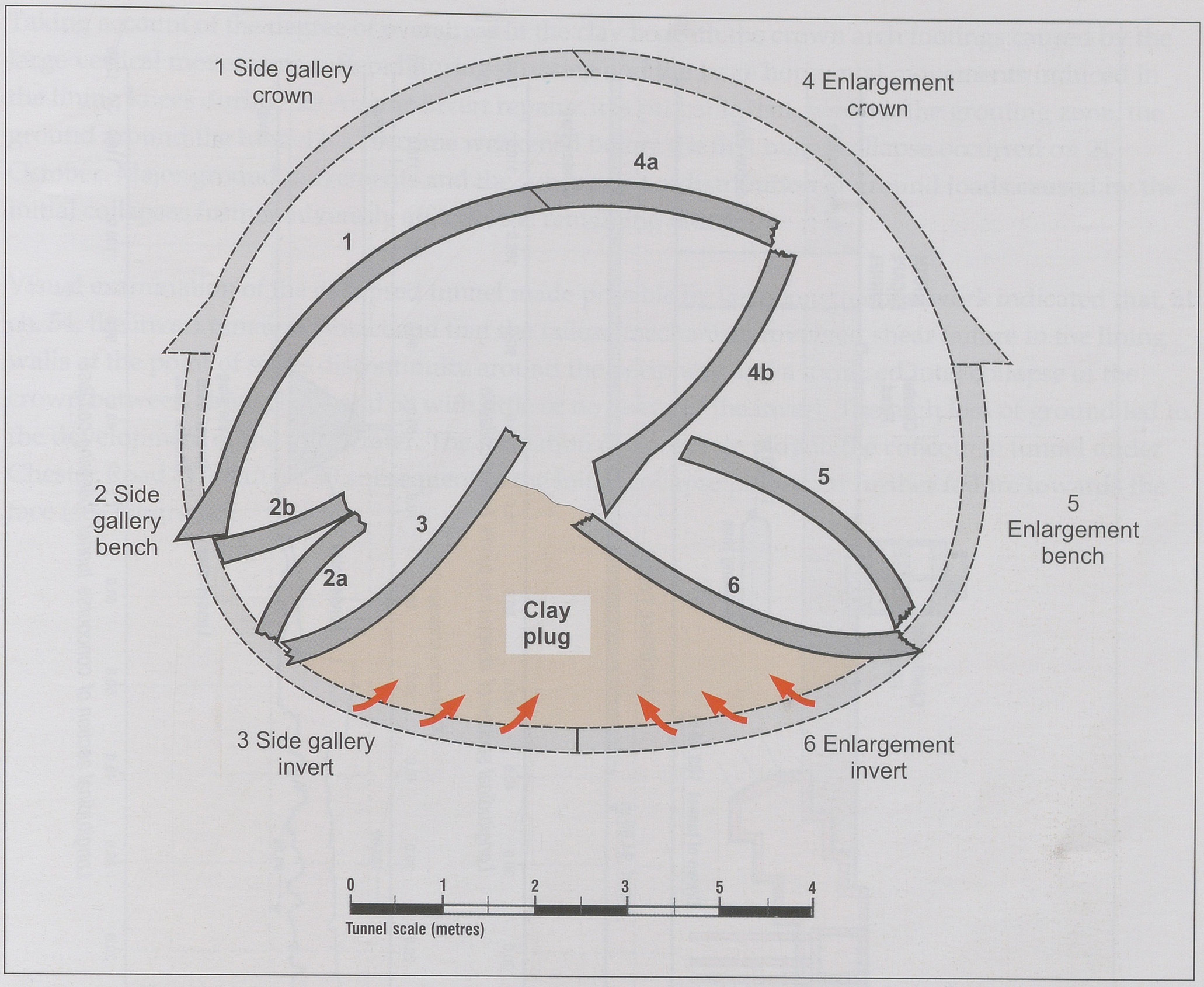


Figure 31 *Postulated failure mechanism for concourse tunnel*

14 The up-line platform tunnel 'north', although distressed, initially remained standing. However, the collapse of the concourse tunnel resulted in a significant redistribution of ground loadings and movement. The up-line platform tunnel collapsed on Saturday 22 October at its junction with the fuel depot shaft cross-passage, causing the formation of a second surface crater.

15 A third surface crater formed on Sunday 23 October. It was remote from the initial collapse and at about ch. 54 where the concourse tunnel had been repaired during August. The volume loss propagated to the surface and caused the crater into which parts of Camborne House were drawn. The concourse tunnel had earlier failed progressively to short of this point by folding around itself (see Figure 32). The repairs from ch. 54 affected this collapse mechanism by creating a predisposition to a discontinuity at this chainage.

16 Loads acting on a sound tunnel are resisted by forces both around and along the lining. At ch. 54 the longitudinal resistance was adversely affected as the defective part of the invert was unable to carry load and, additionally, the extent of the strain induced by grouting was greater at this chainage than at any other (see Figure 25).

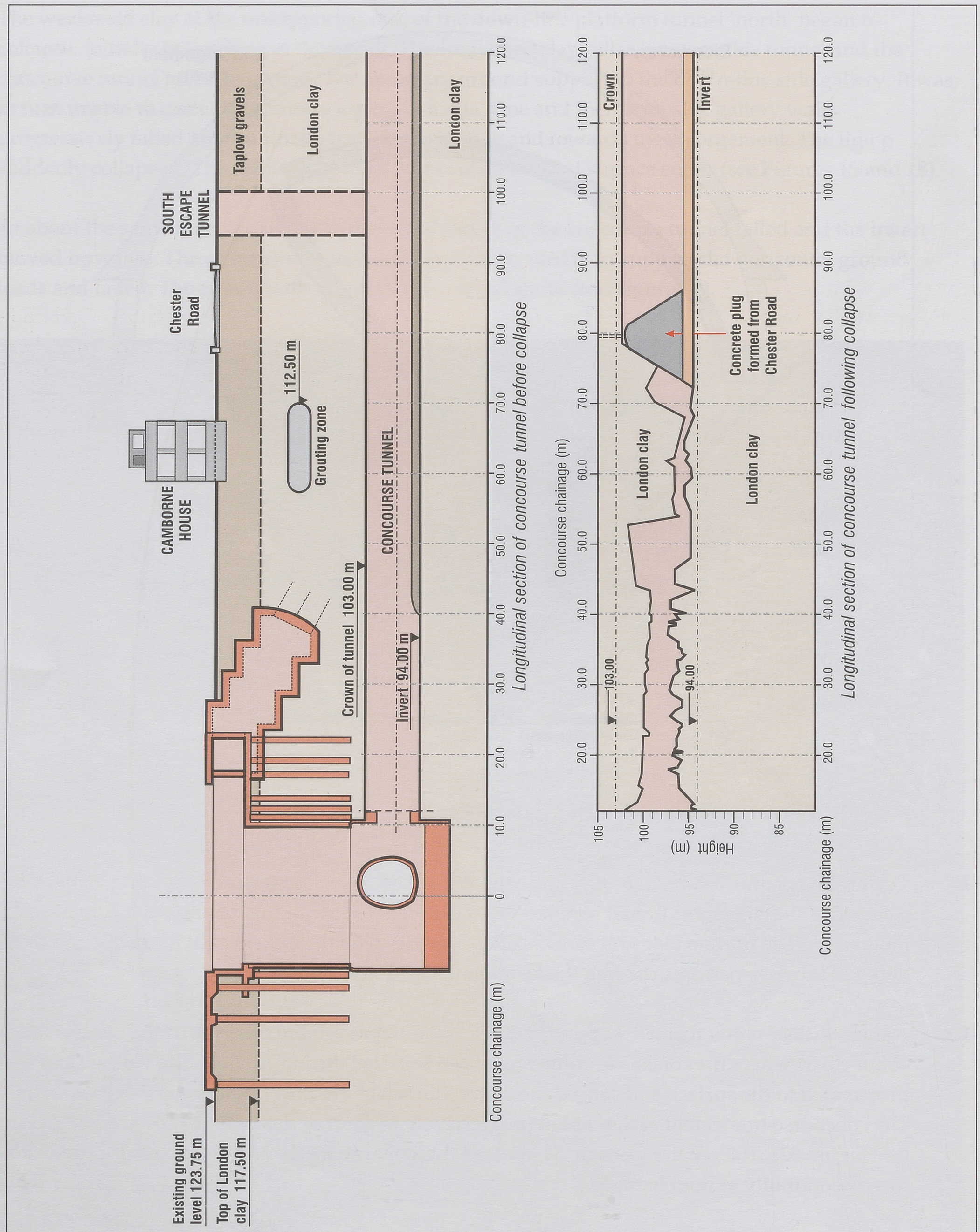


Figure 32 *Concourse tunnel profile following collapse (based upon the upper and lower extent of debris found during re-excavation)*

17 Taking account of the degree of overstress in the clay beneath the crown arch footings caused by the large vertical movements suffered during grouting and the large horizontal movements induced in the lining knees during the August invert repairs, it is probable that, beneath the grouting zone, the ground around the tunnel had become weakened before the first major collapse occurred on 21 October. Major ground movements and the subsequent redistribution of ground loads caused by the initial collapses further adversely affected the remaining lining.

18 Visual examination of the collapsed tunnel made possible by later construction work indicated that, at ch. 54, the invert remained intact and that the failure mechanism involved shear failure in the lining walls at the point of stress discontinuity around the periphery and a localised total collapse of the crown between about ch. 54 and 68 with little or no heave in the invert. The high loss of ground led to the development of the third crater. The formation of a concrete plug in the concourse tunnel under Chester Road at about ch. 80 subsequent to the initial collapse prevented further failure towards the face (see Figure 32).

APPENDIX 5: HSE's NATM Report - principal conclusions

1 Major NATM collapses have occurred worldwide. This finding and recent scrutiny of proposals for NATM in the UK lead HSE to conclude that some safety-critical aspects of NATM design and construction have been poorly understood, and past experience has not been adequately taken into account.

2 NATM tunnel collapses in urban areas can result in major consequences, not just to those working in the tunnel but to members of the public, the infrastructure and the built environment.

3 There will be locations where the consequences of collapse are unacceptable. In such cases alternative solutions should be adopted.

4 There is always some degree of uncertainty in tunnelling design and construction. This can be significant with NATM. A risk-based approach to design and management is required.

5 Safety risks are greatest in tunnel headings. Open faces, a feature of NATM, are hazardous. Linings are more vulnerable to collapse before the ring is closed.

6 Ground investigations throughout must ensure that there is no likelihood of meeting unexpected conditions of a critical nature.

7 A robust design is essential. Design for each element should be fully developed before construction of that element commences. Design modifications should only be used to enhance a robust design.

8 The 'observational method' is a process in which a predetermined design is reviewed during construction. It is not a method of design or design modification. (By way of further explanation, the observations may confirm the adequacy of a design or indicate the need for modification.)

9 An integrated approach should be taken to the design of permanent and temporary works. Design should consider the whole process of NATM tunnel construction.

10 Monitoring is of limited value in the heading and does not ensure face stability. Therefore, every stage in the excavation of the heading and construction of the lining should be designed.

11 The safety of completed sprayed concrete linings depends on monitoring and data interpretation. The design should determine the monitoring regime and contingency actions.

12 The achievement of quality is essential if a NATM project is to be completed successfully.

13 'Buildability' (ease of construction) should be considered in design and construction planning.

14 Contingency plans and emergency procedures are required to deal with adverse events.

15 NATM is heavily dependent on avoiding human failure.

16 NATM tunnels require the deployment of considerable skill and care in investigation, planning, design, construction and monitoring. Clients, designers and constructors should not underestimate the complexity of the task they will face before and during construction.

17 Competency of the NATM team is crucial, and should be assessed.

18 NATM projects do not require skills not already available to the UK construction industry.

19 Provided careful account is taken of all the issues in this review, it has proved possible for NATM work to proceed in safety.

20 The existing statutory provisions, and in particular CDM,[8] provide a comprehensive system for the regulatory control of risk including the assessment of competencies. HSE concludes there is no need for further legislation specifically to address the risks arising from NATM.

21 Tunnels built with NATM linings, when finally completed and fully commissioned, are as safe as those constructed by other means.

APPENDIX 6: Previous HSE involvement in the project

1 HSE's Field Operations Division became aware of the project and contacted BAA's project managers, Taylor Woodrow, in December 1990.

2 Broad schematic design drawings, etc, were obtained and reviewed by HSE's civil engineering specialists. A meeting was subsequently held with BAA, Mott MacDonald and Taylor Woodrow in February 1991. The proposed works and the general approach to managing the project were considered. Detailed issues were also discussed, including the temporary structural integrity of NATM tunnels.

3 HSE again met with Taylor Woodrow in May 1991 to discuss their general approach to health and safety through paperwork systems with particular reference to the NATM trial. A letter subsequently sent dealt with health and safety management, the proposed Management of Health and Safety at Work Regulations and made reference to risk assessment. It also touched on the proposed EC Directive for Temporary and Mobile Construction Sites.

4 Opportunities provided by the trial tunnel in early 1992 led to a number of visits by HSE's specialist civil engineering, occupational hygiene and noise inspectors. Read-over from the Channel Tunnel project was covered by involving the same specialist inspectors. HSE wrote to the parties about a number of matters including the safety of open faces. The trial tunnel was completed without incident and some considerable time later the temporary NATM lining was incorporated into the permanent works.

5 A final review meeting was held with the joint-venture contractor for the trial and Taylor Woodrow at the end of July 1992. HSE subsequently wrote to Taylor Woodrow dealing, among other things, with the forthcoming MHSWR and risk assessment, avoidance and reduction, and also referring to the proposed CDM Regulations.

6 Based upon the lessons learned from the Channel Tunnel, and after discussion with those co-ordinating HSE's inspection of the Jubilee Line Extension Project, it was decided that TBM mechanical safety, vehicle movements (especially underground transport), fire safety, emergency procedures and tally systems would be pursued as priority issues at the Heathrow Project. A major incident when a large dump truck fell down the fuel depot shaft during its construction was investigated.

7 Before Balfour Beatty commenced their contract, the project director and safety manager gave a presentation to HSE and a number of issues were raised in discussion. These did not include the safety of NATM.

8 In mid-1994, HSE visited the factories where the TBMs were being manufactured. A number of

mechanical safety issues were identified and recommendations made to eliminate them. Fire safety issues were also flagged up for further consideration.

9 Site visits by HSE inspectors, including a civil engineering specialist, were made to the T4 NATM works and the car park 5 TBM site on 18 August 1994. CTA was not visited due to the time spent on the TBM. The CTA NATM was seen on 6 September 1994. Issues identified during these visits included TBM safety, manriding, operation of tally systems, fire safety and evacuation procedures. A proposed emergency evacuation exercise planned for 4 November 1994 was discussed. HSE was not told about the major repairs that had recently been concluded nor of other quality problems. On 6 October 1994, HSE paid further visits to car park 5 and Shepiston Lane, the two sites where TBMs were in use, to consider fire safety.

10 BAA had indicated that they proposed to apply the principles of CDM to the project as they envisaged the Regulations would begin to bite before the project was finished. HSE chose to see how this early initiative worked in practice. Meetings were held between March and October 1994 about the development of the health and safety plan, the assessment of competence and aspects of design risk assessment for one small part of the project.

11 HSE's Railway Inspectorate is required by statute to approve new and altered railway works. There were meetings between the Inspectorate, BAA and their consultants on a range of design issues concerning the completed railway works. The adequacy of the temporary NATM lining, either during construction or upon completion, was not an issue.

APPENDIX 7: Legislation current at the time

Health and Safety at Work etc Act 1974 (HSWA)

1 HSWA imposes, among other things, general duties on employers towards employees and others, including members of the public, to ensure that they are protected from risks arising from the employers' activities.

The Management of Health and Safety at Work Regulations 1992 (MHSWR)

2 MHSWR placed duties on employers to assess the risks to which workers and others may be exposed in order to identify what needed to be done to comply with legal requirements.

3 The Approved Code of Practice (ACOP) to the Regulations gave guidance on risk assessment principles, including a hierarchy of preventive measures to determine appropriate responses to assessed risks. Appendix 2 to the CDM ACOP sets out the hierarchy in the context of construction.

4 MHSWR placed other duties on employers. These included duties to:

- make and put into effect health and safety arrangements for planning, organising, controlling, monitoring and reviewing the steps necessary to deal with issues identified through risk assessment;
- provide health surveillance for employees;
- appoint competent person(s) to assist in securing compliance with health and safety legislation;
- establish emergency procedures;
- provide health and safety information to employees;
- co-operate and co-ordinate with other employers and the self-employed;
- take steps as 'host employers' to secure the health and safety of others, including the self-employed, who work for them; and
- take account of employee capabilities and provide them with health and safety training, including on recruitment, on transfer to new work, at changes of responsibilities and when new work equipment, technology and working methods are adopted.

5 The 1992 Regulations and ACOP have since been revoked and replaced by the Management of Health and Safety at Work Regulations 1999 and a new ACOP.

The Construction (Design and Management) Regulations 1994 (CDM)

6 CDM first came into force on 31 March 1995, five months after the collapse at Heathrow. There were transitional provisions such that the requirements on designers did not apply until 1 August

1995 in respect of any design where preparation started before 31 March 1995. The Regulations were fully in force from 1 January 1996. CDM places duties on clients, planning supervisors, designers, and principal and other contractors. There are synergies with other regulations such as MHSWR and the Safety Representatives and Safety Committees Regulations 1977. CDM is comprehensively explained in the ACOP to the Regulations *Managing health and safety in construction*, ISBN 0 7176 0792 5.

The Construction Regulations 1961-1989

7 Detailed requirements specific to the construction industry at the time of the collapse were contained in five codes of regulations variously made between 1961 and 1989. These were:

- The Construction (General Provisions) Regulations 1961;
- The Construction (Lifting Operations) Regulations 1961;
- The Construction (Working Places) Regulations 1966;
- The Construction (Health and Welfare) Regulations 1966;
- The Construction (Head Protection) Regulations 1989.

8 The 1961 and 1966 Regulations have since been revoked and replaced by the Construction (Health, Safety and Welfare) Regulations 1996 (CHSW) and the Lifting Operations and Lifting Equipment Regulations 1998 (LOLER). Reference should be made to other HSE publications such as *Health and Safety in Construction*, HSG150, ISBN 0 7176 1143 4 for details of the wide-ranging obligations that can arise.

APPENDIX 8: Glossary

Compass points

'Compass' north runs diagonally across the fuel depot worksite. For simplicity, the contract presumed that the platform tunnels ran north-south and assigned 'north' to the direction of travel away from the fuel depot shaft and towards the M4, Shepiston Lane and London; likewise, 'south' was towards car park 3, Terminal 3 and Terminal 4.

Abbreviations and glossary

Agent	Manager responsible for a part of the construction works
BAA plc	Title of the publicly quoted company, previously known as the British Airports Authority
Balfour Beatty	Balfour Beatty Civil Engineering Limited, a wholly owned subsidiary of BICC
Bench	Mid-section of a tunnel between the crown and invert
Car park 5	A surface car park on the south side of the airport where the trial tunnel was constructed
CDM	Construction (Design and Management) Regulations 1994
Chainage (ch.)	A point along the axis of a tunnel identified by its distance from a fixed reference point. For the CTA concourse tunnel, the reference point was the centre of the fuel depot shaft (see Figure 2)
Compensation grouting	Placing grout within a ground mass to compensate for surface grouting settlement, brought about by loss of ground at a tunnel heading, as it occurs (see Appendix 1)
Crown	Highest point of the tunnel cross-section
CTA	Central Terminal Area
Enlargement	New tunnel built alongside an earlier one so as to increase the cross-section
Eye	Opening at the junction between a tunnel and a shaft (or similar structure)
Forepoling	Insertion of rods or tubes into the extremities of the crown face so that the rods are supported from within the tunnel and project above and beyond the area to be excavated to form a means of temporary support
Geoconsult	Geoconsult Ges MBH of Salzburg, Austria (now Geoconsult ZT Ges MBH)
Grout jacking	The use of relatively large volumes of grout injected at high pressure into the ground to lift a structure that has settled (see Appendix 1)
HSC	Health and Safety Commission
HSE	Health and Safety Executive
in situ	Cast in place
Invert	Lowest part of the tunnel cross-section (derived from the term 'inverted arch')
Knee	Point on the tunnel at mid-height below the axis

Lattice girder	Curved steel rib formed of interconnected bars
London clay	Principal clay layer in the London basin
Method statement	Written description of work to be carried out
MHSWR	Management of Health and Safety at Work Regulations 1992
MMS	Main monitoring station
NATM	New Austrian Tunnelling Method
NATM Report	HSE's report *Safety of New Austrian Tunnelling Method (NATM) Tunnels*[1]
NVT	North ventilation tunnel at T4
Piezometer	An instrument for measuring pore water pressure, that is the pressure of water in the ground
Rebound	Shotcrete material which rebounds from a surface during placement
Risk assessment	Formalised means for identifying hazards and assessing risks
SDN	System defect notice
Shield	Tunnelling machine having a protective ring equal to the diameter of the tunnel, which can be advanced to protect people from falling ground and sometimes having excavating and segment-placing machinery
Shotcrete	Special quick-setting concrete mix sprayed under pressure
Side gallery	Pilot tunnel smaller than the final section
Spalling	The breaking away of material from a surface
T4	Terminal Four
TAM	Tube-à-manchette, a grouting tube used in compensation grouting
Taylor Woodrow	Taylor Woodrow Management Contracting Limited
TBM	Tunnel boring machine

APPENDIX 9: Members of the Heathrow Enquiry Board and the Project Investigation Team

Heathrow Enquiry Board

Mr M S Nattrass, CBE (Chair), Health and Safety Executive, HM Chief Inspector of Construction
(**Mrs S Caldwell** replaced Mr M S Nattrass on his retirement from HSE)

Sir Alan M Muir Wood, Consultant to Sir William Halcrow and Partners Ltd. Independent Member

Professor C R I Clayton, Department of Civil and Environmental Engineering, University of Southampton. Independent Member

Mr S S J Robertson, CBE, Health and Safety Executive, HM Chief Inspecting Officer of Railways
(**Mr V P Coleman** replaced Mr S S J Robertson on his retirement from HSE)

Mr K L Twist, Health and Safety Executive, HM Chief Inspector of Mines
(**Mr B Langdon** replaced Mr K L Twist on his retirement from HSE)

Mr D Mitchell, Health and Safety Executive, Head of Division A, Safety Policy Directorate
(**Mr J Grubb** replaced Mr D Mitchell)

Mr P G Jones, Health and Safety Executive, Head of Technology Division of the Directorate of Science and Technology
(**Mr M A Fountain** replaced Mr P G Jones on his retirement from HSE)

Heathrow Project Investigation Team

Dr R G Evans (Team Director), Health and Safety Executive, Field Operations Directorate

Mr M Thurgood, Health and Safety Executive, Field Operations Directorate

Dr M Harrison, Health and Safety Executive, Field Operations Directorate

Dr D Hill, Health and Safety Executive, HM Railway Inspectorate

Mr J M Anderson, Health and Safety Executive, Technology Division of the Directorate of Science and Technology (since retired from HSE)

Mr M H Senyard, Health and Safety Executive, Field Operations Division (since retired from HSE)

Mr D Sweeney, WS Atkins Consultants Limited

Mr G Lance, WS Atkins Consultants Limited

Mr I Morrison, WS Atkins Consultants Limited

Miss S Lemon, Health and Safety Executive, Field Operations Directorate

Mr A Maxey, Health and Safety Executive, Safety Policy Directorate

Mrs D Garton, Health and Safety Executive

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Figure 31 Postulated failure mechanism for concourse tunnel

Figure 32 Concourse tunnel profile following collapse (based upon the upper and lower extent of debris found during re-excavation)

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